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THE
ASTROPHYSICAL JOURNAL

An International Review of Spectroscopy and Astronomical Physics

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THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME XIX JANUARY 1904 NUMBER 1

THE BLACK BODY AND THE MEASUREMENT OF EXTREME TEMPERATURES.[1]

By ARTHUR L. DAY and C. E. VAN ORSTRAND.

W. MICHELSON, in a recent address published in the *Journal of the Russian Physico-Chemical Society* of St. Petersburg,[2] says:

> You are all aware, of course, that the Carnot-Clausius principle, that is to say, the so-called second law of thermodynamics, is one of the most general and most fruitful laws of contemporary physics. But it is also one of the most difficult to understand and to master in the concrete. Every series of arguments connecting this law either with experimental data or with equations of analytical mechanics, or, finally, with the principles of the theory of probabilities — in every case the light falls only on one side of the law, and no formula has yet been found to express completely its full scope.

---

[1] Read before the Philosophical Society of Washington, November 7, 1903, by the authors.

[2] Vol. XXXIV, No. 5, pp. 155–201, 1902 (Russian). It is very unfortunate that this paper has not been translated into some one of the more familiar languages of scientific literature. W. Michelson was the first to attempt to formulate a general equation for the distribution of energy in the continuous spectrum, and his critical examination of the steps by which the study of ether thermodynamics has advanced in the fifteen years since that time is itself a splendid contribution to the progress of the science. The authors are indebted to this paper all through the present discussion, and only regret that limits of space and title prevent the reproduction of considerable portions of it *in extenso*. The extracts here reproduced were translated by MR. ROBERT STEIN, of the U. S. Geological Survey.

The problem in ether thermodynamics offered by the spectrum is singularly analogous to the mechanics of a heated body. If we were able to follow out every detail of the motion of a single molecule of a heated body, we should undoubtedly find it conforming to the differential equation of Lagrange. And if we could select out a particular train of polarized, monochromatic oscillations from some spectrum, it would probably be completely expressed by Maxwell's differential equation. There is no reason to doubt that these solutions fully interpret the elementary phenomena as far as our present opportunities for verification extend. And yet an actual aggregate of such heated molecules, like a bundle of simple oscillations, in a very short period of time becomes so complicated that the integrating constants are hopelessly varied and distributed. There is no recourse but to statistical methods and average magnitudes. The unordered character of the processes occurring in both mechanical and electromagnetic phenomena is not due to infringement of the elementary differential equations of the one science or the other, but solely to the enormous complexity of the phenomena.

Tentative advances and partial solutions of the problem of radiation have been made in considerable number, greatly stimulated by the construction recently of an experimental black body capable of such exact manipulation as to outstrip, for the moment, the analytical advance. The steps in this development have almost all been contributed from abroad, and they have followed each other with such rapidity that those of us who have been compelled to follow their progress from a distance have hardly been able to see what has stood and what has fallen in the keen contest between the mathematical and experimental development. The obvious importance of any generalization which will enable us to determine the thermal condition of a remote body (the temperature of the Sun, for example), or one so hot that our usual laboratory apparatus cannot approach it without courting destruction, will be sufficient ground for scrutinizing the theories which have been propounded, examining carefully in how far they are supported by experimental data, and with what degree of probability they can be extrapolated to extreme temperatures to meet the present needs of several branches of science.

The "black body"[1] lies at the very foundation of the quantitative study of radiant energy. It was first defined by Kirchhoff[2] in 1860, as a body which absorbs *all* the radiation which falls upon it—which reflects none and transmits none.[3] The experimental black body did not come until thirty-five years later (Wien and Lummer, 1895),[4] although Kirchhoff himself stated the conditions essential to its physical realization very explicitly in his original memoir. A radiation identical with that which an ideal black surface would emit, he says, is realized within every inclosed cavity in an opaque body, all parts of which have the same temperature. The properties of this radiation do not depend upon the properties of the walls forming the inner surface of the cavity, provided the latter have a finite light-emitting power for every wave-length (*i. e.*, are not perfect reflectors). Messrs. Wien and Lummer therefore simply prepared a hollow sphere, coated inside with lamp-black for low temperatures and oxide of iron or uranium for the higher temperatures, and provided with a single small opening. The principle will appear at once from the figure (Fig. 1). So much of the radiant energy as is not absorbed where it first impinges (*a*) upon the surface, must meet it again and again until the last surviving increment disappears.[5] No surface has ever been found which fulfils Kirchhoff's definition of blackness

---

[1] The name "black body" is now in general use to describe a *perfectly absorbing* body. It begins to emit light when the temperature reaches about 525° C. The terms "black body" and "black radiation" are therefore somewhat misleading at the higher temperatures.

[2] G. KIRCHHOFF, "Ueber das Verhältniss zwischen dem Emissionsvermögen und dem Absorptionsvermögen der Körper für Wärme und Licht," *Pogg. Ann.*, **109**, 275, 1860.

[3] " . . . . welcher alle Strahlen, die auf ihn fallen, vollkommen absorbirt, also Strahlen weder reflektirt noch hindurchlässt."

[4] W. WIEN and O. LUMMER, "Methode zur Prüfung des Strahlungsgesetzes absolut schwarzer Körper," *Wied. Ann.*, **56**, 451, 1895.

[5] Strictly speaking, some rays will escape through the opening, however small. This of course involves a small error, but it is of negligible magnitude.

The part which the black body plays in the study of radiation will appear in a moment. In the paper above referred to, Kirchhoff fully established the first great law[1] in the thermodynamics of the ether, or, perhaps more strictly speaking, he was the first to make a general application of the second law of thermodynamics to radiation. He states it in this way: The ratio between the radiating and absorbing power for a given wave-length and temperature is the same for all bodies, and must therefore be a universal function of temperature and wave-length.[2] Thus for every substance emitting purely calorific radiation,

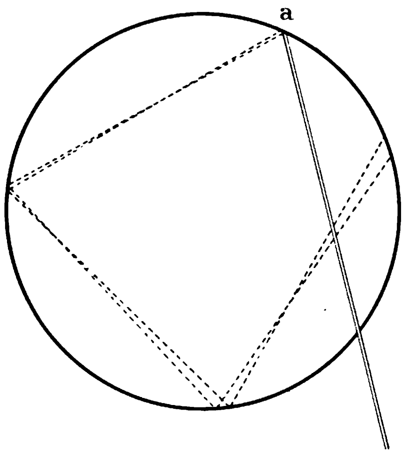

FIG. 1.

$$\frac{i_\lambda}{a_\lambda} = e_\lambda = f(\lambda,\ T)\ ,$$

i_λ = radiating power for wave-length λ,
a_λ = absorbing power for wave-length λ,
e_λ = radiating power for wave-length λ of the black body;

and for total radiation,

$$\frac{I}{A} = E.$$

Suppose we write the latter relation

$$\frac{I}{E} = A,$$

I is the energy of the total radiation from a given body, E the same function for an ideal, perfect radiator or black body

---

[1] An excellent demonstration of Kirchhoff's law will be found in DRUDE'S *Theory of Optics*, English translation, Longmans, Green & Co., 1902, p. 496.

[2] "Das Verhältniss von Emissions- und Absorptionsvermögen, bezogen auf die gleiche Wellenlange und die gleiche Temperatur, ist für alle Körper das gleiche."

(Kirchhoff's definition), $\frac{I}{E}$ is then simply the number which represents the radiating power of the given body in terms of its unit, the perfect radiator, and is numerically equal to the absorbing power (A), which may be defined as the ratio between the quantity of radiant energy retained by the body and the total amount received. The function of the black body is therefore clear; it serves as the standard or unit of measurement which makes out of the study of radiation a quantitative science.

e_λ (energy radiated by a black body for the wave-length λ) is frequently called "Kirchhoff's function." He did not define the form of the function, but reasoned that it must be a simple one, being the same for all bodies, and therefore a natural law. He believed that the fundamental laws of nature were all simple.

Clausius,[1] who first formulated the second law of thermodynamics, was also greatly interested in its application to radiation. He proved that the Kirchhoff relation could not be independent of the surrounding medium without violating the second law, and finally that no phenomenon of heat radiation can produce motion in contradiction to the second law. This paper appeared in 1864 and, with the classical paper of Kirchhoff, forms the sound basis of a rapidly developing science.

In developing the electromagnetic theory of light, Maxwell[2] found that one of the consequences of his analysis was a resultant pressure in the direction of transmission, numerically equal to the energy per unit of its volume. Although the force was very small, Maxwell thought that a suitable light body suspended in a vacuum ought to show it. Several of these attempts were made at that time, but, owing to the relatively great disturbances in the residual gas, the phenomenon could not be experimentally established. The discovery was of considerable significance to astronomy, but no immediate application to physical problems appeared.

---

[1] R. CLAUSIUS, "Die Concentration von Wärme- u. Lichtstrahlen u. die Grenzen ihrer Wirkung," *Pogg. Ann.*, 121, 1–44, 1864.

[2] *Electricity and Magnetism*, chapter on "Electromagnetic Theory of Light."

Three years later, in 1876, Bartoli[1] arrived at the conclusion that light waves must exert a pressure in the direction of their propagation, by a process of thermodynamic reasoning. His line of argument is entirely different from Maxwell's, and is approximately this: To suppose equilibrium between energy of radiation and the temperature, it is necessary to assume a synonymous functional dependence between the latter and the energy per unit volume. If this density be increased by diminishing the volume while T remains unchanged, energy must necessarily be communicated to the adjacent walls of the vessel so long as the equilibrium is not re-established. His system is reviewed by W. Michelson[2] as follows:

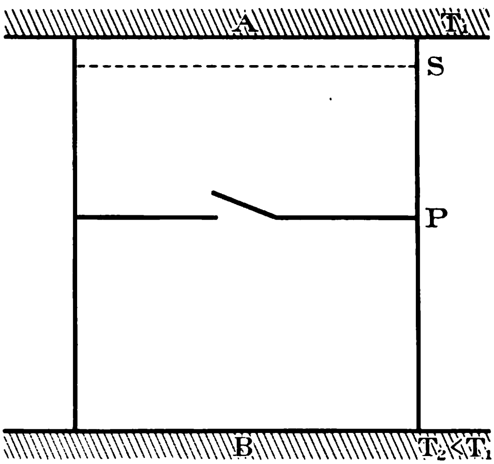

FIG. 2.

Imagine two perfectly black bodies A and B (Fig. 2), having temperatures T_1 and $T_2 < T_1$, to include between them a perfectly white (diffusely reflecting) cylinder equipped with a piston P and a screen S which may be used to screen A, and both impervious to radiation. Lower the piston with the valve open, slip the screen in front of A, then raise the piston with the valve closed and withdraw S. It is plain that any amount of heat in the form of diffuse radiant energy can be transferred in this way from the colder body B to the warmer body A. According to the second law, this process is only possible when work is done, which in this case must be sought in the raising of the piston with the valve closed. And this work will suffice as compensation for the transfer of the energy only in case the diffuse radiation exerts a pressure on the piston which is proportional to its density. Thus purely thermodynamic reasoning has led to the same conclusion which Maxwell reached in his electromagnetic theory of light. Bartoli also prepared elaborate experiments in an effort to verify his conclusion experimentally, but was unable to eliminate the disturbances due to the surrounding gas.

---

[1] BARTOLI, *Sopra i movimenti prodotti dalla luce e dal calore.* Le Monnier, Florence, 1876. See also *Wied. Ann.*, **22**, 31, 1884. A third proof is given by GALITZINE, *Wied. Ann.*, **47**, 470–495, 1892; *Phil. Mag.*, (5) **35**, 113-126, 1893, and a fourth by H. PELLAT, *Journ. d. Phys.* for July 1903.

[2] *Loc. cit.*, 1902.

After another three-year interval, light was thrown upon the problem of radiation from a different source. Stefan[1] noticed that in some experiments of Tyndall upon the radiation from glowing platinum wire between the first red heat (525° C.) and full white heat (estimated at 1200° C.), the radiated energy was proportional to the fourth power of the absolute temperature. He verified this relation (which bears his name) upon existing experimental data (Dulong and Petit, de la Prevostaye and Desains, and others) and published it as the conclusion toward which all the data gathered up to that time clearly pointed. This law plainly asserted, without qualification, that for a given temperature the quantity of radiant energy emitted by all solid bodies was the same, although its spectral composition was known to differ widely. Apparent support was found for this in the very generally accepted earlier law of Draper (1847),[2] that red heat begins in all solid bodies at the same temperature (525° C.). Recently more exact methods and measurements[3] have shown that neither of these generalizations is more than roughly true. Different bodies have been found to possess different radiating powers and to reach red heat at different temperatures.[4]

It remained for Boltzmann[5] in 1884 to bring these threads

---

[1] J. STEFAN, "Ueber die Beziehung zwischen der Wärmestrahlung und der Temperatur," *Wien. Akad. Ber.*, II. Serie. **79**, II. Abth., 391, 1879.

[2] J. W. DRAPER, *Amer. Jour. Sci.*, (2) **4**, 1847; *Phil. Mag.*, (3) **30**, 1847; *Scientific Memoirs*, London, 44, 1878.

[3] H. F. WEBER, EMDEN, LUMMER and associates, BOLTZMANN (theoretical considerations), and others.

[4] No body can reach red heat *before* the black body.

[5] L. BOLTZMANN, "Ableitung des Stefan'schen Gesetzes, u.s.w. aus der electromagnetischen Lichttheorie," *Wied. Ann.*, **22**, 31 and 294, 1884.

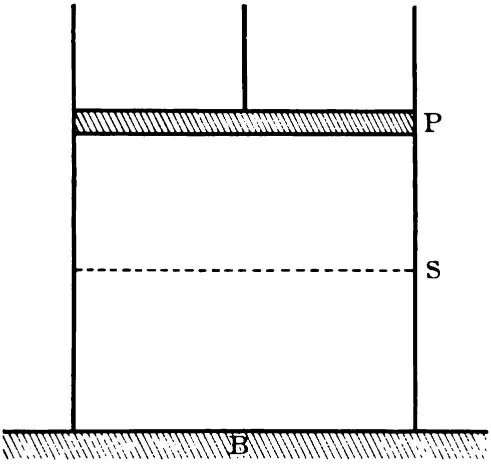

Fig. 3.

together and to interpret the real meaning of Stefan's law with the help of the light-pressure which Maxwell and Bartoli, each from a different standpoint, had reasoned must exist, but of which they were not able to find experimental evidence. Boltzmann imagines a cylinder (Fig. 3) similar to Bartoli's, but open at one end, in which a piston incloses radiant energy of the temperature of the heat reservoir (the black body *B* closing end of cylinder). He then interposes an impervious screen between the piston and reservoir, and allows the piston to move away from the fixed screen, producing a radiational adiabatic expansion. Now, in order to treat this under the second law of thermodynamics ($\int \frac{dQ}{T} = 0$), the process had to be reversible, and to make it reversible it was necessary to assume that for identical values of the total density of the radiation its *wave-length composition* will always be identical, irrespective of the manner in which the change of density proceeds — whether by fall of temperature or by adiabatic expansion. This assumption, which is most important for the demonstration, was not proved until nine years later by W. Wien.[1] Boltzmann then proceeded, after a manner closely analogous to the demonstration of the resolution of pressures along the co-ordinate axes in a perfect gas, to prove that the pressure of completely diffuse radiation on the surface of the piston is exactly equal to one-third of the density. From these two important theorems, a few steps of simple formulation brought him to the so-called Stefan law,[1]

---

[1] W. Wien, "Eine neue Beziehung der Strahlung schwarzer Korper zum zweiten Hauptsatz der Warmetheorie," *Sitzungsber. Berl. Akad.*, **6**, 55–62, 1893.

$$E=\int_0^\infty e_\lambda \, d\lambda=\sigma T^4,$$

but with an important difference. Stefan promulgated his relation as true of all bodies without regard to the quality of the radiation (color); Boltzmann deduces it only for *complete* or *black radiation.* The Stefan-Boltzmann law as finally established (1884) may be stated in words as follows: The energy of completely diffuse (black) radiation is directly proportional to the fourth power of the absolute temperature.

It only remains to add the evidence bearing upon the law, which has been gathered in the interval since the black body

---

[1] The derivation is given briefly by W. WIEN in "Les lois théoriques du rayonnement," *Rapport, congrès international de physique,* **2**, 20, as follows:

$$dQ=dU+dW.$$

dQ = differential of the radiant heat entering the cylinder.
dU = increase of internal energy.
dW = external work.

$$u=v\psi.$$

v = volume.
ψ = density of energy (intensity per unit volume).

$$dW=pdv=\frac{1}{3}\psi dv \text{ (Boltzmann).}$$

$$dQ=d(v\psi)+\frac{1}{3}\psi dv=vd\psi+\frac{4}{3}\psi dv.$$

An integrating factor of the right-hand member is $\psi^{-\frac{1}{4}}$, of the left, $\frac{1}{T}$, hence

$$T=b\sqrt[4]{\psi}, \quad \psi=\frac{T^4}{b^4}=\sigma T^4 \text{ (Stefan Boltzmann law).}$$

The differential of the entropy is

$$dS=\frac{dQ}{T}=\frac{v}{b}\psi^{-\frac{1}{4}}d\psi+\frac{4}{3b}\psi^{\frac{3}{4}}dv=d\left[\frac{4}{3b}v\psi^{\frac{3}{4}}\right].$$

Integrating

$$S=\frac{4}{3b}v\psi^{\frac{3}{4}}+\text{const.}$$

In adiabatic expansion

$$\psi v^{\frac{4}{3}}=\text{const.},$$

which is exactly analogous to Poisson's

$$pv^k=\text{const.}$$

in the thermodynamics of gases. The relation of the two heat capacities is supplied by the number $\frac{4}{3}$ as a direct consequence of the fact that the light-pressure of black radiation is equal to $\frac{1}{3}$ of its density.

became a laboratory instrument (1895). A single table taken from Professor Lummer's measurements[1] will serve to show the character of the experimental verification:

Absolute Temperature Observed	σ	Absolute Temperature Calculated	T.Obs. – T. Calc.
373°.1	127.0	374°.6	−1°.5
492.5	124.0	492.0	+0.5
723.0	124.8	724.3	−1.3
745.0	126.6	749.1	−4.1
810.0	121.6	800.5	+3.5
868.0	123.3	867.1	+0.9
1378.0	124.2	1379.0	−1.0
1470.0	123.1	1468.0	+2.0
1497.0	120.9	1488.0	+9.0
1535.0	122.3	1531.0	+4.0
Mean	123.8		

The observed temperatures are in terms of the Holborn-Day gas thermometer scale,[2] extrapolated above 1150° C. with the help of platinum—platin-rhodium thermo-elements.[3]

The last two years have also witnessed the experimental verification of the Maxwell-Bartoli light-pressure theorem. Lebedew[4] in 1901 not only succeeded in showing the existence of a pressure in the direction of propagation of light, but measured it and found it to be within about 20 per cent. of the value anticipated in the Maxwell-Bartoli analyses. Quite independently of Lebedew, Nichols and Hull[5] have been at work upon the same problem, and with such refinement of method that they have just been able to announce perfect agreement with the theoretically established value within the limits of their observation errors (about 1 per cent). Their observations include measurements upon light passing through air of various pressures, through red glass and through water.

---

[1] See O. LUMMER, "Le rayonnement des corps noirs," *Rapports congr. intern. de phys.*, **2**, 41 (Gauthier-Villars, Paris, 1900), where the full literature will be found.

[2] LUDWIG HOLBORN and ARTHUR L. DAY, "Ueber das Luftthermometer bei hohen Temperaturen," *Ann. der Phys.*, **2**, 505, 1900; Engl. transl., *Am. Jour. Sci.*, (4) **10**, 171, 1900.

[3] LUDWIG HOLBORN and ARTHUR L. DAY, "Ueber Thermoelektricität einiger Metalle," *Sitzungsber. Berl. Akad.*, 691, 1899; Engl. transl., *Am. Jour. Sci.*, (4) **8**, 303, 1899.

[4] P. LEBEDEW, *Ann. d. Phys.*, **6**, 433-458, 1901; *Rapports congrès international*, Paris, 1900, 133 *seq.*

[5] E. F. NICHOLS and G. F. HULL, preliminary publication, *Phys. Rev.*, November 1901; final results, July and August 1903; ASTROPHYSICAL JOURNAL, **17**, 315-351, June 1903.

If this review has been clear, we now see that this important general law of ether thermodynamics boasts exceptionally complete theoretical development, supported by experimental data both in its main hypothesis and in its conclusion. It is therefore very generally regarded as established.

The law of Stefan-Boltzmann gives us the total energy of the spectrum of the black body, but says nothing in regard to the energies of the component monochromatic radiations (e_λ, Kirchhoff's function), their relation to temperature, and their distribution in the spectrum. Even before this time attempts to solve the distribution of the energy in the spectra of various bodies had been made,[1] but the first particularly noteworthy effort was due to W. Michelson[2] in 1887. In the previous year S. P. Langley[3] had published some observations upon the general features of the energy curves obtained from the Sun, the arc light, and some other sources, and from these Michelson endeavored to reach a general theory. His working hypothesis was that the continuity of the spectrum emitted by solid bodies could be explained only by complete disorder in the vibrations of their atoms, and that each periodic change in the motion of an atom produces a wave of the same period in the surrounding ether. Then he assumed that Maxwell's law of the most probable distribution of velocities among a great number of molecules is valid for solids, and, by very ingenious reasoning, based largely upon the theory of probabilities,[1] deduced a general equation for the black body:

---

[1] The distribution of energy in the spectra of particular solid bodies and of the Sun was measured much earlier (Langley) and received some theoretical consideration (E. v. LOMMEL, *Wied. Ann.*, **3**, 251, 1877).

[2] "Essai théorique sur la distribution de l'énergie dans les spectres des solides," *Journ. de la Soc. Phys., Chim. russe*, (4) **19**, 79, 1887; *Journ. de Phys.*, (2) **3**, 467, 1887.

[3] S. P. LANGLEY, *Ann. d. Chim. et Phys.*, (6) **9**, 433–506, 1886.

$$E_\lambda = c_1 T^{\frac{3}{2}} f(T) \lambda^{-(2p+4)} e^{\frac{-c_2}{\lambda^2 T}}$$

Or, when combined with Stefan's law,

$$E = c_1 T^{\frac{3}{2}} \lambda^{-6} e^{\frac{-c_2}{\lambda^2 T}}$$

The apparent support of this deduction furnished by the Langley data proved to be illusory, as the Langley tables were obtained from prismatic spectra and did not apply to relations in the normal spectrum.

Other attempts quickly followed this, but they contributed little to the advancement of the subject, and, with perhaps one exception, are not of interest now. The condition for maximum radiation in Weber's equation (1888)[2] required that the wavelength for which the energy is a maximum should be shorter as the temperature increases:

$$\lambda_{\mathrm{max.}} T = \text{const.},$$

i. e., with increasing temperature the greatest intensity of radiation approaches the visible spectrum. This appears to have been the first publication of a relation which is characteristic of the more important equations which have followed and which has received abundant independent verification from experiment.

The next really important attempt to derive a general equation to express the distribution of spectral energy, was made, after an interval of eight years, by W. Wien in 1896.[3]

Although this long interval produced no general distribution equation of importance, it is marked by two important steps toward it—the demonstration of the so-called "displacement law" by W. Wien (1893)[4] and the achievement of an experimental black body by Wien and Lummer (1895).[1] The latter represented little more than the practical carrying out of the directions of Kirchhoff in his original memoir, to which reference has already been made, but it marks an epoch in the study of radiation. It at once became possible to verify the general relations which had been developed in considerable number, and furnished initiative and direction to further analytical effort.

---

[1] One point in this demonstration of probabilities, which here appears for the first time, is of more than incidental importance. Michelson supposes each particle to have a fixed position of equilibrium about which it constantly oscillates as in the usual theory of solid bodies. He then demonstrates from simple hypotheses that the most probable path of such particles approximates very closely to successive diameters of its sphere of activity.

[2] H. F. WEBER, *Sitzungsber. Berl. Akad.*, II, 933 957, 1888.

[3] W. WIEN, "Ueber die Energievertheilung im Emissionsspektrum des schwarzen Körpers," *Wied. Ann.*, **58**, 662, 1896.

[4] *Loc. cit.*

The Wien displacement equation had also been long desired and partly anticipated. Boltzmann had assumed, but not proved, that there was no difference in the *composition* of black radiation, whether its energy-density were increased by adiabatic compression or by increase of temperature. Wien explained this by an ingenious application of Doppler's principle to radiant heat. His reasoning is briefly this: If the radiation from a black body is contained within perfectly white (diffusely reflecting) walls, a diminution of volume can be accomplished only by doing work against the pressure of the radiation, and is accompanied by an increase in the density (energy per unit volume) of the radiation. The second law of thermodynamics requires that the spectral composition of the compressed radiation, be the same as though the increase in the density had been produced by increasing the temperature. Both theory (Boltzmann)[2] and experiment (Weber)[3] had shown that wave-lengths were shortened in a simple ratio by increasing the temperature. Wien demonstrated that compressing inclosed radiant energy in this way must involve Doppler's principle, and that this was necessary and sufficient to account for the shortening of all wave-lengths in the same ratio. The relation of color and temperature he found to be[4]

$$\frac{\lambda}{\lambda_0} = \frac{\theta_0}{\theta} \; ;$$

therefore, as Wien himself expresses it, "when the temperature increases, the wave-length of every monochromatic radiation diminishes in such a manner that the product of the temperature and the wave-length is constant." From this equation Weber's maximum relation,

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[1] *Loc. cit.* [2] 1884, *loc. cit.* [3] 1888, *loc. cit.*

[4] Given in DRUDE'S *Theory of Optics*, Engl. trans., 516-522, 1902.

$$\lambda_{\text{max.}} T = \text{const.} ,$$

appears in its proper context as a special case. And if we go farther, as Wien did, and combine the equation with the one which represents the Stefan-Boltzmann law, a new relation follows:

$$E = T^5 \phi (\lambda T) ,$$

in which the energy appears not merely as a general function of T and λ, but as a specific function of T and of the product λT. From this combination of the displacement law with that of Stefan, it is possible to calculate the distribution of energy in the spectrum of the black body for any temperature whatever, provided only that the distribution is known for a single temperature. Of course, this conclusion served to bend every effort to the determination of the energy — wave-length relation for a particular temperature, a problem to which ten full years have now been given without reaching a wholly satisfactory result.

Before proceeding to the discussion of the more important efforts in this direction, attention should be called to one weak link in the chain of reasoning thus far. Wien's combination of Stefan's law with his own displacement law involves assumptions which, without the practically unanimous support of experiment, must be open to criticism. How, says Michelson,[1] are we to apply the Stefan-Boltzmann law to *monochromatic* radiation, for which it has never been proved true? And again, what is the status of the term "temperature" when applied to free monochromatic radiation in the ether, which is not in equilibrium with any hot body? It is, indeed, a long analytical step from completely diffuse radiation in equilibrium with its envelope, to free monochromatic radiation. And yet the inferred analogy seems to be justified *a posteriori* by experiment. The expression

$$E_{\text{max.}} T^{-5} = \text{const.} ,$$

which is obtained by combining the Wien and Stefan laws, has been fully verified by the experiments of Lummer, Paschen,

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[1] *Loc. cit.*, 1902.

Rubens, Pringsheim, Wanner, Kurlbaum, and others. A representative table of experimental values from Lummer[1] follows:

T Absolute	λ_m	E_m	$\lambda_m T$	$\frac{E_m}{T^5}$	T Computed	Difference Degrees
621°2	4.53	2.026	2814	2190	621°3	+0°1
723.0	4.08	4.28	2950	2166	721.5	−1.5
908.5	3.28	13.66	2980	2208	910.1	+1.6
998.5	2.96	21.50	2956	2166	996.5	−2.0
1094.5	2.71	34.0	2966	2164	1092.3	−2.2
1259.0	2.35	68.8	2959	2176	1257.5	−1.5
1460.4	2.04	145.0	2979	2184	1460.0	−0.4
1646.0	1.78	270.6	2928	2246	1653.5	+7.5
		Mean	2940	2188		

Some recent observations by Paschen[2] establish the constant even more sharply:

T Absolute	λ_m	$\lambda_m T$	E_m	$\frac{E_m}{T^5 \times 10^{15}}$
876°4	3.333	2914	0.637	1.232
875.0	3.328	2911	0.642	1.252
1052.2	2.781	2926	1.667	1.293
1053.7	2.770	2919	1.660	1.277
1055.2	2.777	2929	1.643	1.255
1337.4	2.188	2926	5.454	1.275
1347.4	2.172	2927	5.499	1.238
1352.7	2.159	2920	5.665	1.251
1357.4	2.157	2929	5.797	1.258
1567.9	1.858	2913	12.28	1.296
1580.6	1.846	2918	12.26	1.242
	Mean	2921		1.268

We may now return to the general law of distribution of energy and W. Wien's second important contribution (1896) to the study of radiation, for he was also the first to attack the main issue which he had so clearly pointed out with his displacement equation. Like Michelson, Wien draws heavily upon the theory of gases for analogies from which to formulate a general theory of radiation for the black body. No one has yet succeeded in deducing a theory of spectral distribution from established generalizations alone. It has always been found necessary to postulate important special relations which must then be judged according to the accuracy with which quantitative experimental results are interpreted. Wien makes the following special hypotheses:[1]

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[1] *Rap. congr. int.*, **2**, 82.

[2] "Ueber das Strahlungsgesetz des schwarzen Körpers." *Ann. d. Phys.*, (4) **4**, 277, 1901.

1. In a gas which sends out radiant energy, each molecule emits only radiations of a single wave-length. The vibration period is a function of the molecular velocity only.

2. The intensity of the radiation included between two neighboring wave-lengths is proportional to the number of molecules which emit radiations of that particular period.

From these and the law of Maxwell, which Michelson had employed, together with his own displacement law, Wien developed a new equation:

$$\phi_\lambda d\lambda = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}} .$$

Compared with Michelson's treatment of the problem, two important differences appear in that of Wien — the return to thermodynamic reasoning throughout, and the use of the displacement law, which was demonstrated long after Michelson's paper appeared.

It will throw much light on the theoretical problem, and on the character and consequences of the arbitrary hypotheses of which Wien and others have been obliged to make use, if we quote briefly from Michelson's criticism of Wien's assumptions in the recent article referred to at the beginning of this paper, bearing in mind that six years of great theoretical and experimental activity had passed since Wien derived his law, and sixteen years since Michelson's own earlier publication:

> . . . . But with the formulation of this law (Wien's), as given by the author himself and accepted, among others, by Planck, I do not entirely agree.
>
> The point at issue is this, that Wien affirms that completely unordered (black) radiation consists of innumerable multitudes of different monochromatic radiations which, he says, are merely mixed mechanically and possess each its own individual energy; on varying the temperature, each by itself

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[1] *Rap. congr. int.*, 2, 35.

follows the law of Stefan, and besides, according to the "displacement law," changes its wave-length, λ, in inverse proportion to the absolute temperature. The condition of thermal (radiational) equilibrium W. Wien and Planck find in the *identical temperatures* attributed to all elementary monochromatic radiations. But to assert this is, in my opinion, to carry too far the analogy between black radiation and a mixture of a multitude of different gases.

In the first place, to speak of "temperature" of monochromatic radiation is possible only very conditionally and with reservations, because such radiation cannot be in thermal equilibrium with any actually hot body. In the second place, I hold it as certain that, in black radiation, the different monochromatic constituent parts of it have not each its own individual existence, but continually mingle their energies. If such an uninterrupted exchange of energy does not take place among the different radiations, I do not see how we can rationally explain the Kirchhoff function e_λ as synonymous with the dynamic stability of completely unordered radiation. . . . . In this respect, the diffuse radiation inclosed in an opaque envelope differs essentially from the radiation which is freely propagated in the ether. Here a determined period of oscillation is indissolubly connected with every element of energy, and the latter is completely characterized by just that period, together with a particular amplitude and azimuth of polarization. Upon removal of the source, and upon passing through the different centers, the amplitude and polarization may change; the period alone (except under a few rare conditions) remains unchanged. It then brings us information even from the different stellar worlds which give spectra of thin lines. But in the diffuse radiation of a black body there are no traces of any lines, there are no indissoluble ties connecting the period with the individual portions of radiant energy. . . . . Just as the heat equilibrium of gas, characterized by the law of Maxwell, is only maintained, because of the uninterrupted exchange of velocity among the different molecules of the gas, so also the law of Kirchhoff is verified by the uninterrupted exchange of energy between oscillations of different periods.

At first, after Wien's law appeared, there seemed to be good reason for believing that the problem was finally solved. A few weeks before its publication, a mass of new experimental data had been published by Paschen[1] for a number of substances closely approximating to the black body. To these the formula was at once applied and successfully. Planck[2] soon after succeeded in deducing the Wien formula from quite different assumptions, using the electromagnetic theory of light, whereas Wien had depended chiefly upon thermodynamics. Meanwhile Paschen had continued his experimental measurements with an actual black body, and his results, contained in two papers,[1] agreed perfectly with the Wien-Planck law.

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[1] "Ueber Gesetzmässigkeiten in den Spektren fester Körper." *Wied. Ann.*, 58, 455, 1896.

[2] "Ueber irreversible Strahlungsvorgänge," etc., *Sitzungsber. Berl. Akad.*, 1897, 57, 715, 1122; 1898, 449, and 1899, 440; also *Ann. d. Phys.*, 1, 69 and 719, 1900.

But Wien's law had come at a time (one year after the development of the experimental black body) when very exact experimental data had to be reckoned with, and so the twofold derivation of the law with the confirmatory experiments of Paschen did not suffice to establish it without a question.

The story is a most interesting one. First Professor Lummer, who with Wien himself built the first black body, was unable with a very effective plant (at the *Reichsanstalt*), to confirm Paschen's results, nor would his data fit the Wien-Planck equation. For the constants c_1 and c_2 of the formula he obtained:[2]

λ	$1.21\ \mu$	$1.96\ \mu$	$2.20\ \mu$	$3.03\ \mu$	$4.50\ \mu$
c_2	13510	13810	14240	14800	16510
$c_1 . 10^{11}$	1007	1210	1440	1771	2201

and later with Pringsheim,[3] over a greater range of wave-lengths:

λ	$1.21\ \mu$	$4.50\ \mu$	$8.8\ \mu$	$12.3\ \mu$	$17.9\ \mu$
c_2	13510	16510	18500	24800	31700

in which not only large but systematic variations from the constant value appear. Then Beckmann[4] made a similar determination for the wave-length[5] $\lambda = 24\,\mu$ and found $c_2 = 26{,}000$.

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[1] "Ueber die Vertheilung der Energie im Spektrum des schwarzen Körpers bei niederen Temperaturen," *Berl. Akad. Ber.*, 405, 1899. "Ueber die Vertheilung der Energie im Spektrum des schwarzen Korpers bei hoheren Temperaturen," *ibid.*, 959, 1899. ASTROPHYSICAL JOURNAL, **10**, 40, 1899; **11**, 288, 1900.

[2] *Rapports congr. international, loc. cit.*

[3] *Verh. d. Deutsch. Phys. Ges.*, **2**, 1900.

[4] Inaugural Dissertation, Hannover, 1898.

[5] RUBENS has since shown (*Wied. Ann.* **69**, 570, 1899) that the substances used as sources of radiation by Beckmann must have yielded two wave-lengths, $\lambda = 24\,\mu$ and $\lambda = 32\,\mu$—which is immaterial in this connection however.

Then Lummer and Pringsheim[1] employed a sylvin prism and made further measurements between the wave-lengths 12μ and 19μ and the temperatures -190° to $+1550^\circ$, and found c_2 to vary with the temperature as well as with the wave-length. Still another careful set of measurements by Rubens and Kurlbaum,[2] extending to 50μ, corroborated the foregoing (see tables, p. 22). And finally Paschen himself,[3] upon repeating his experiments, found that he was able to represent only the short wave-lengths by the Wien-Planck equation.

Notwithstanding this pressure of adverse experimental evidence and the somewhat strained theoretical reasoning, the Wien formula is difficult to displace. Both in its hypotheses and in its formulation it is the simplest and most straightforward of the expressions which have been proposed to represent the distribution of spectral energy in black radiation. In that part of the spectrum in which the maximum intensity occurs, and for a sufficient distance on either side of it to include by far the greater part of the total radiation expressed by Stefan's law, the Wien equation represents the distribution of the intensity exceedingly well. It is among the longer waves of the infra-red, from 6μ on as far as measurements have been made (50μ), that the formula totally fails.[4] It therefore offers no hope of successful extrapolation to inaccessible temperatures.

Equations of similar character to that of Wien have been developed by Thiesen,[5] Rayleigh,[6] Jahnke,[7] and others, to which some reference will be made farther on. They represent efforts to reproduce the experimental results more faithfully than the

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[1] O. LUMMER and E. PRINGSHEIM, *Zeitschrift für Instrumentenkunde*, **20**, 149, 1900; *Verh. Deutsch. Phys. Ges.*, February 1900.

[2] "Ueber die Emission langwelliger Wärmestrahlen durch den schwarzen Körper bei verschiedenen Temperaturen," *Sitzungsber, Berl. Akad.*, 929-941, 1900; *Ann. d. Phys.*, **4**, 649-666, 1901.

[3] *Verh. d. Deutsch. Phys. Ges.*, **2**, 202, 1900, footnote; *Ann. d. Phys.*, **4**, 277-298, 1901.

[4] See tables, p. 22.

[5] "Ueber das Gesetz der schwarzen Strahlung," *Verh. d. Deutsch. Phys. Ges.*, **2**, 65-70, 1900.

[6] *Phil. Mag.*, **49**, 539, 1900.

[7] *Ann. d. Phys.*, **3**, 283-297, 1900.

Wien formula was found to do, by more or less empirical modifications of it. They may therefore be regarded as nearer approximations than Wien's in some cases, and possess more accessible constants in some, but they follow the same reasoning and cannot be said to have contributed anything further to the final solution of the problem.

Planck has a somewhat different method of approaching the subject of the distribution of energy in the radiation of the black body. It is hardly possible even to sketch the plan of his elaborate structure within the limits of this brief examination of the subject. He starts out in his first paper[1] with Maxwell's equation for the propagation of electromagnetic oscillations in the ether, and establishes the conditions for perfectly diffused rectilinear light. He then imagines an inclosed space filled with such disordered radiation to contain a great number of small, ideal, electric resonators, which are then supposed not to interfere with one another. Each resonator acquires some final oscillatory state depending only upon the intensity of the radiation of its particular period which falls upon it. For the monochromatic oscillations of each period he assumes the existence of a great number of independent resonators of the same period. He assumes further that within each such system of resonators and electromagnetic waves of a particular period, notwithstanding incomplete and irregular intermingling of phase, amplitude and azimuth of polarization and direction of light, there is established some stationary state depending on the character of the total energy of the given period. Out of this artificial system Planck has evolved two theories. In the first[2] he determined arbitrarily the entropy of such an ideal resonator in a field of completely diffused radiation, and obtained the same formula which W. Wien had deduced from thermodynamic considerations. He has now abandoned this theory. In the second[3] he follows certain ideas of Boltzmann's on the probability of recurrence of certain states in an assumed system of atoms or molecules, and defines the entropy of one of the resonators by analogy between this assumed system and his own system of electromagnetic oscillations.

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[1] "Irreversible Strahlungsvorgänge," *loc. cit.*, also *Ann. d. Phys.*, **1**, 69, 1900; "Entropie u. Temperatur strahlender Warme," *ibid.*, 719.

[2] 1897, *loc. cit.*

[3] "Ueber eine Verbesserung der Wien'schen Spektralgleichung," *Verh. d. Deutsch Phys. Ges.*, **2**, 202, 1900; *Sitzungsber. Berl. Akad.*, 544, 1901.

It is scarcely possible at this time to offer a fair criticism of Professor Planck's result. His formula fits all the more reliable observations which have been made over the entire range of accessible wave-lengths with unexceptionable exactness (see table below), but he frankly states that his definition of entropy is only one of an infinite number of possible definitions in such a system of electromagnetic oscillations, and that it was chosen with the experimental observations before him, because it was the simplest one which fitted. His definition is therefore in a measure "after the fact," and inasmuch as it is built upon a strongly ideal and exceedingly intricate system, it has not, so far, been regarded as possessing the essential characteristics of a final solution. Michelson, in the critical article before referred to, accepts it provisionally, though not with confidence. "The future only can show," he says, "whether it is merely a new degree of approximation which in time will meet the same fate that has overtaken the earlier spectral formulæ." Wien deprecates the extraordinarily complicated character of the reasoning and says it should be greatly simplified. It should be added that Planck has compared his expression for "electromagnetic entropy" with Boltzmann's determination of the entropy of a gas, and drawn some interesting inferences upon the masses of molecules and atoms, and on the magnitude of the charge carried by one electron.[1] The order of the quantities obtained is the same as obtained by the other methods.

A comparative table from Rubens and Kurlbaum[2] shows very clearly the superiority of the Planck formula in representing the experimental data for the longer wave-lengths:

[1] M. PLANCK, " Ueber d. Elementarquanta d. Materie u. d. Electricität," *Ann. d. Phys.*, (4) **4**, 564–566, 1901.

[2] " Anwendung der Methode der Reststrahlen zur Prüfung des Strahlungsgesetzes," *Ann. d. Phys.*, (4) **4**, 649, 1901; also ASTROPHYSICAL JOURNAL, **14**, 335, 1901.

TABLE I.

$\lambda=8.85\ \mu$.

Absolute Temperature *T*	*E* Obs.	*E* Wien	*E* Rayleigh	*E* Planck
0°	....	− 1.96	− 1.00	− 1.41
100	− 1.6	− 1.96	− 1.00	− 1.41
200	− 1.5	− 1.82	− 0.92	− 1.31
300	....	± 0.10	+ 0.10	+ 0.1
373	+ 3.4	+ 4.07	+ 2.21	+ 3.0
500	+ 13.5	+ 16.5	+ 9.60	+ 12.4
800	+ 53.5	+ 60.5	+ 44.3	+ 50.3
1100	+102.0	+107.0	+ 96.7	+ 99.8
1273	+132.0	+132.0	+132.0	+132.0
1400	+154.0	+147.7	+160.0	+154.6
1700	+212.5	+182.3	+229.0	+213.5

$\lambda=24.0\ \mu$ and $31.6\ \mu$.

0	....	− 42.4	− 10.7	− 15.4
85	− 15.5	− 41.0	− 10.5	− 15.0
193	− 9.4	− 26.8	− 7.4	− 9.3
293	0	0	0	0
523	+ 30.3	+ 50.6	+ 25.3	+ 28.8
773	+ 64.3	+ 88.9	+ 58.3	+ 62.5
1023	+ 98.3	+114.5	+ 94.4	+ 96.7
1273	+132.0	+132.0	+132.0	+132.0
1523	+167.0	+145.0	+174.5	+167.5
1773	+201.5	+155.0	+209.0	+202.0
∞	....	+226.0	+ ∞	+ ∞

$\lambda=51.2\ \mu$.

0	....	−121.5	− 20.0	− 23.8
85	− 20.6	−107.5	− 19.0	− 21.9
193	− 11.8	− 48.0	− 11.5	− 12.0
293	0	0	0	0
523	+ 31.0	+ 63.5	+ 28.5	+ 30.4
773	+ 64.5	+ 96.0	+ 62.5	+ 63.8
1023	+ 98.1	+118.0	+ 97.0	+ 97.2
1273	+132.0	+132.0	+132.0	+132.0
1523	+164.5	+141.0	+167.0	+166.0
1773	+196.8	+147.5	+202.0	+200.0
∞	....	+194.0		

The discussion of the title of Planck's second formula to be regarded as an adequate and final solution of the problem of spectral energy distribution may properly be left to the future. It represents all the trustworthy experimental observations of record, to the highest temperatures at which it has been found possible to measure (1550° C.) and is the only one of the spectral distribution equations which has not yet been shown to be defective in its theory, or its application, or both.

To summarize, then, there are four quantitative relations defining the radiation from the black body, which are founded upon generally accepted theoretical reasoning; their constants are accessible to experiment and have been established within reasonable limits of error by all the leading experimental scientists who have contributed to the problem thus far:

(1) The Stefan-Boltzmann relation,

$$E = \int_0^\infty e_\lambda \, d\lambda = \sigma T^4 ,$$

representing the total radiant energy emitted by a black body as a simple function of the temperature.

(2) and (3) Two relations consequent upon W. Wien's theorem that with increasing temperature all wave-lengths are shortened in inverse ratio to the absolute temperature:

$$2. \qquad \lambda_{\text{max.}} T = \text{const.}$$

$$3. \qquad E_{\text{max.}} T^{-5} = \text{const.}$$

The same relations also define the conditions at the energy maximum in the distribution formulæ of Planck, Wien, and the others.

(4) Planck's second law of distribution of energy in the black spectrum,

$$E = c_1 \lambda^{-5} \left(e^{\frac{c_2}{\lambda T}} - 1\right)^{-1} .$$

Before making application of these laws to the problem of estimating inaccessible temperatures, it will contribute much to a clear understanding of the relation of the formulæ which have been examined, to each other, if we leave the chronological development for a moment and briefly consider the general character and limitations of the radiation function — a subject upon which the literature of radiation is singularly barren.[1]

With the help of the theory of functions it is possible to construct expressions which will represent all the necessary conditions of the problem and at the same time permit of a detailed analysis of the component functions of which the general form is made up.

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[1] An investigation of this character has been made by DR. P. G. NUTTING; see ASTROPHYSICAL JOURNAL, **12**, 208, 1900, and *Phil. Mag.*, (6) **2**, 379, 1901.

Experiment shows that for any particular temperature (T) there is a corresponding distribution of energy in the spectrum of the black body. If we plot the energy of the radiation (E) for any particular wave-length as ordinate, and the corresponding wave-length (λ) as abscissa, we obtain for any temperature (T_1, T_2. . . .T_n) curves o a_1 $T_1\infty$, o a_2 $T_2\infty$, ... o a_n $T_n\infty$ of the form indicated in the diagram. All of the curves representing the relation between radiant energy and wave-length are of this general form. Experiment also shows that the locus of the maxima (a_1, a_2, ...a_n) in these curves approaches the $+y$ axis with increasing temperature. From the form of these experimental curves, we may say further that the x axis must be tangent to the curve at the points $\lambda = 0$ and $\lambda = +\infty$. Between these points there are no zeros, no negative values, and no infinities—the ordinates are always finite and positive.

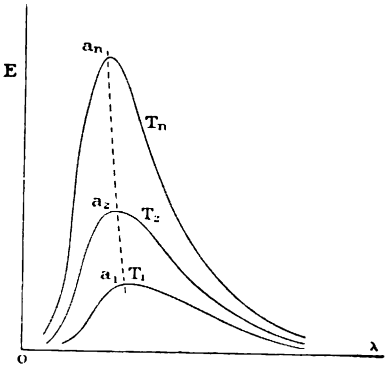

FIG. 4.

In order to define the functions which represent the curves having these properties, it is convenient to define the reciprocal, which evidently also contains no zeros, no negative values, and no infinities except at the points $\lambda = 0$ and $\lambda = +\infty$. We can now apply well-known theorems in the theory of functions and classify the possible expressions according to their singularities. There will be three classes according as the functions contain singularities which are accidental, essential, or a combination of both accidental and essential. They are given in Forsyth's notation in column 2 of the table as shown on the following page.

Character of Singularity	$E^{-1}=\frac{1}{f(\lambda)}$ (Forsyth's Notation)	$E=f(\lambda)$	Limiting Conditions
Accidental	(I) $\dfrac{\prod_{r=1}^{m}(\lambda-a_r)}{\prod_{r=1}^{m-p}(\lambda-c_r)}$	(1) $\dfrac{\lambda^q(a_o+a_1\lambda+\ldots.a_r\lambda^r)}{(b_o+b_1\lambda+\ldots b_s\lambda^s)}$	$q+r<s$ $q>1$
Essential	(II) $\prod_{i=1}^{n}(\lambda-a_i)^{c_i}\prod_{i=1}^{n}e^{g_1\left(\frac{1}{\lambda-a_i}\right)}$ (III) $G(\lambda)+\sum_{r=1}^{n}G_r\left(\frac{1}{\lambda-a_r}\right)$	(2) $cf(\lambda)e^{-g(\lambda)}e^{-g_1\left(\frac{1}{\lambda}\right)}$ (3) $\left[cf(\lambda)e^{g(\lambda)}e^{g_1\left(\frac{1}{\lambda}\right)}+P\left(\lambda,\frac{1}{\lambda}\right)\right]^{-1}$	$g(\lambda)>0$ $g_1\left(\frac{1}{\lambda}\right)>0$
Accidental and Essential	(IV) $\dfrac{\sum_{i=1}^{n}G_i\left(\frac{1}{\lambda-c_i}\right)}{\sum_{i=1}^{n}G_{n+i}\left(\frac{1}{\lambda-c_i}\right)}$	(4) $c\lambda^n e^{-g(\lambda)}$ (5) $\left[c\lambda^{-n}e^{g(\lambda)}+P\left(\lambda,\frac{1}{\lambda}\right)\right]^{-1}$ (6) $c\lambda^{-n}e^{-g_1\left(\frac{1}{\lambda}\right)}$ (7) $\left[c\lambda^n e^{g_1\left(\frac{1}{\lambda}\right)}+P\left(\lambda,\frac{1}{\lambda}\right)\right]^{-1}$ (8) $\ldots\dfrac{P+G}{P_1+G_1}\ldots\ldots$	$n>1$ $g(\lambda)>0$ $n>0$ $g_1\left(\frac{1}{\lambda}\right)>0$ Order of denom. > order of num.

The expressions in column 3 are obtained from the corresponding expressions in column 2 after substituting the boundary conditions. The necessary substitutions and transformations will be considered in detail for each particular class.

(1) *Accidental singularities.*—The first equation is an application[1] of the theorem that a function containing accidental singularities only must have as many zeros as infinities. $\lambda=+\infty$ is a pole of order p. There are m zeros (a_r) and $(m-p)$ poles (c_r) in the finite part of the plane. Since there are no undulations in the curve, the quantities a_r and c_r must be either zero or negative. Expressing the indicated product relations and

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[1] FORSYTH'S *Theory of Functions*, 2d ed., Cor. III, p. 81.

taking the reciprocals, we may write the equation in the form (I), in which $q + r < s$.

(2) *Essential singularities.*—Equation III is obtained from II by the addition of polynomial or transcendental terms.[1] Equation II is the most general simple product relation[2] between λ and E^{-1}. For real variables, c_i is any constant, positive or negative, integral or fractional. a_i is the point at which the function becomes discontinuous. When $a_i = +\infty$, theory requires that there be a factor

$$F_1(\lambda) = ce^{g(\lambda)} .$$

And when $a_i = 0$, the factor is

$$F_2(\lambda) = \lambda^{c_1} e^{-g_1\left(\frac{1}{\lambda}\right)} .$$

The reciprocal of the product of these two expressions

$$E = c\lambda^{-c_1} e^{-g(\lambda)} e^{-g_1\left(\frac{1}{\lambda}\right)}$$

is the most general product relation in a single term, which has the required zeros. Since c_i may have any value, we may put

$$f(\lambda) = \lambda^{-c_i}(b_0 + b_1\lambda + \ldots b_n\lambda^n)$$

and then replace the above equation by

$$E = cf(\lambda)e^{-g(\lambda)} e^{-g_1\left(\frac{\lambda}{1}\right)} .$$

$f(\lambda)$ is necessarily polynomial. $g(\lambda)$ and $g_1\left(\frac{1}{\lambda}\right)$ may be either polynomial or transcendental. The roots of the polynomials must occur at the origin or in the negative part of the plane. In general, we know that $g(\lambda)$ must vanish or reduce to a constant when $\lambda = 0$ and become infinite when $\lambda = + \infty$. Similarly $g_1\left(\frac{1}{\lambda}\right)$ must become infinite for $\lambda = 0$, and must vanish or reduce to a constant when $\lambda = + \infty$. $g(\lambda)$ and $g_1\left(\frac{1}{\lambda}\right)$ must therefore always be greater than zero.

(3) *Accidental and essential singularities.*—Equation (IV)[3] is the most general form of functions of this type. It may be composed of equations of the forms (I), (II), and (III), and may, in certain cases, contain only accidental or essential singularities.

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[1] *Loc. cit.*, p. 113.

[2] *Loc. cit.*, pp. 110–117.

[3] *Loc. cit.*, pp. 122–124.

The exponent of λ must be positive in equation (4), and negative in equation (6). The denominator of (8) must be of an order higher than the numerator.

Limiting conditions.—The equations (1–8) include curves which intersect the x axis in addition to those which have the x axis for a tangent at the points $\lambda = 0$ and $\lambda = +\infty$. In order to eliminate the former, we impose the condition that the derivative $\left(\frac{dE}{d\lambda}\right)$ must vanish with the function at these points. The last column contains the required conditions. They are readily determined by inspection.

The condition at the maximum.—We have now obtained all the curves of the required form. It remains to select such only of these curves as have their maximum points on a certain locus which may be expressed as a function of λ and T. Both theory and experiment indicate (Wien's displacement law) that this locus is a function of the product (λT), but it is not necessary to limit the investigation to this particular case.

To impose any condition at the maximum in equations (2–7) it is sufficient to make

$$\frac{\partial}{\partial\lambda}\left[cf(\lambda)\,e^{g(\lambda)}\,e^{g_1\left(\frac{1}{\lambda}\right)} + P_1(\lambda) + P_2\left(\frac{1}{\lambda}\right)\right] \equiv F(\lambda, T) = 0 .$$

The exponents $g(\lambda)$ and $g_1\left(\frac{1}{\lambda}\right)$ must necessarily contain the required function $F(\lambda, T)$, hence

$$(a) \qquad c\frac{\partial}{\partial\lambda}f(\lambda) + cf(\lambda)\left[\frac{\partial}{\partial\lambda}g(\lambda) + \frac{\partial}{\partial\lambda}g_1\left(\frac{1}{\lambda}\right)\right] + \frac{\partial}{\partial\lambda}P_1(\lambda) + \frac{\partial}{\partial\lambda}P_2\left(\frac{1}{\lambda}\right) \equiv F(\lambda, T) = 0 .$$

That is, we obtain any required condition at the maximum by putting the corresponding function in the exponents, and then determining the polynomials f, P_1, and P_2 in such manner that equation (a) reduces to a sum of constant terms or to the required function of λ and T.

There are two important special cases, viz.:

$$P_1(\lambda) + P_2\left(\frac{1}{\lambda}\right) = \text{const. or } kf(\lambda) .$$

Substituting in (*a*) we have

$$(b) \qquad \left[c+k\right]\frac{\partial}{\partial\lambda}f(\lambda)+cf(\lambda)\frac{\partial}{\partial\lambda}\left[g(\lambda)+g_1\left(\frac{1}{\lambda}\right)\right]\equiv F(\lambda,\ T)=0\ ,$$

in which $c+k$ is replaced by c for the first case. If $f(\lambda)$ is a monomial, as appears from Stefan's law, equation (*b*) becomes

$$g(\lambda)+g_1\left(\frac{1}{\lambda}\right)\equiv F(\lambda,\ T)=\text{constant}\ .$$

Hence for these special cases the condition at the maximum is determined by the exponents $g(\lambda)$ and $g_1\left(\frac{1}{\lambda}\right)$, and is independent of the factor T in the monomial $f(\lambda)$.

Suppose we now put

$$\lambda^m T^n=\text{constant}.$$

$$f(\lambda)=\lambda^p T^q=\frac{1}{k}\left[P_1(\lambda)+P_2\left(\frac{1}{\lambda}\right)\right]$$

then (3) may be written,

$$(c) \qquad E=\left[c_1\lambda^p T^q\left(e^{g(\lambda^m T^n)}e^{g_1\left(\frac{1}{\lambda^m T^n}\right)}+k\right)\right]^{-1}.$$

And to obtain Planck's last equation, for example, we have only to insert those special relations which appear from the foregoing to be established:

$p=5$ (Stefan-Boltzmann law)
$q=g(\lambda^m T^n)=0,\ k=-1$
$m=n=1$ (Wien's displacement law)

when

$$E=\left[c_1\lambda^{-5}\left(e^{\frac{c_2}{\lambda T}}-1\right)\right]^{-1} \qquad \text{[Planck]}$$

All the other spectral distribution equations are obtainable by inspection in the same way by introducing the characteristic limitation of each in the following:

$$g(\lambda^m T^n)=k=0,\quad f(\lambda)=\lambda^p T^q,\quad \lambda^m T^n=\text{constant.},$$

then

$$E = c_1 T^{\frac{3}{2}} \lambda^{-6} e^{-\frac{c_2}{\lambda^2 T}} \qquad \text{[Michelson]}$$

$$E = c_1 \lambda^{-2} e^{aT - \frac{1}{b^2 \lambda^2 T^2}} \qquad \text{[Weber]}$$

$$E = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}} \qquad \text{[Wien]}$$

$$E = c_1 (\lambda T)^{\frac{1}{2}} \lambda^{-5} e^{-\frac{c_2}{\lambda T}} \qquad \text{[Thiesen]}$$

$$E = c_1 T \lambda^{-4} e^{-\frac{c_2}{\lambda T}} \qquad \text{[Rayleigh]}$$

and

$$E = c_1 \lambda^{-4} T e^{-\frac{c}{(\lambda T)^v}} \quad 1.2 < v < 1.3 \qquad \text{[Jahnke]}$$

Kövesligheţy's equation[1]

$$E = \frac{A \lambda^2 T^4}{(\lambda^2 T^2 + c^2)^2}$$

is a special form of (1).

With but one exception, all of the equations that have been deduced to represent the relations between radiated energy and wave-length, are seen to be very special cases of (7) or (c), in which $g(\lambda) = 0$. If the number of constants is limited to two in this way, by placing $g(\lambda)$ or $g_1\left(\frac{1}{\lambda}\right)$ equal to zero, the equation (c) is the most general relation possible of this type. Greater generality might be obtained by means of equation (8) or by introducing other conditions at the maximum in (7). Planck's equation therefore represents, in this direction, the greatest generality obtainable with but two physical constants, the Stefen-Boltzmann and Wien (displacement) relations.

It would be perfectly possible to define the emission function completely, provided the boundary conditions could be physically defined. The equations which have been deduced have a zero of infinite multiplicity at the origin, and a zero of finite multiplicity at $\lambda = +\infty$. The latter becomes finite when $g(\lambda)$ is put equal to zero in (3). If this can be shown to be a necessary condition, and if a definite physical meaning can be assigned to these zeros, the required function is completely determined by means of function theory alone in equation (7). Equation (5) is the complementary equation with a zero of finite multiplicity at the origin and of infinite multiplicity at infinity, while equation (3), just discussed, represents the general case with both zeros of infinite order.

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[1] R. v. KÖVESLIGHETY, *Grundzüge einer theoretischen Spectralanalyse*, Halle, 1890.

The question now arises whether the temperature of the Sun or of inaccessible volcanic openings can in any proper sense be measured, or even effectively estimated, with the help of the laws we have been considering. It is not usual to apply the same reasoning in attempting to answer this question, which would be used in studying the temperature of the incandescent lamp, for example. The Sun is so completely inaccessible to the common methods of pyrometry, and, moreover, its temperature has so important a rôle in the fundamental conclusions of geology, meteorology, and astronomy, that a new method of estimating it, even if only indirectly or imperfectly applicable, is accustomed to be pressed into service with little question and the exceptional conditions put forward in benevolent extenuation of the outcome if necessary. This has been done with the laws of black radiation.[1] There are many papers, and very recently even text-books, which apply the equations of the black body directly to the measurement of the solar temperature, with no more justification than the fact that we have well-founded and experimentally verified laws of radiation, and therefore have but to apply probable corrections for the absorption which the solar radiation may have suffered before reaching us, to obtain the probable solar temperature.

Against this simple interpretation of the problem there are two serious objections which we certainly are not justified in overlooking, whatever attitude we subsequently choose to assume toward them.

(1) The radiation from the Sun is certainly not pure temperature radiation, but partakes of the character of luminescence,

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[1] Some computations of the solar temperature based upon recent determinations of the constants in the equations of the black body are appended at the end of the paper.

between which and the black body no temperature relation has ever been found.

(2) The temperature of the Sun is certainly so high as to require at least a fivefold extrapolation of the temperature scale upon which the estimate is usually based—an operation which, for a function like temperature, it is difficult to interpret theoretically and which can hardly be called measurement practically.

As long ago as 1847, when Draper[1] published his conclusion that solid bodies begin to emit luminous radiation of the same wave-length at the same temperature, he excepted lime, marble, fluorspar, and such substances as emit radiant energy in no apparent relation to the temperature. Radiation of this character is familiar enough from the glow of the fire-fly and the phosphorescence of decaying vegetable matter, to the radiation sent out from more or less rarified gases during electrical discharges through tubes, and the large class of phenomena in which the source of the radiant energy is not heat, but chemical or photo-chemical change. In all these, radiant energy is emitted and varies widely both in wave-length and intensity with little or no corresponding change in the temperature.

Nor is the bounding line between these two great classes of radiation in the least indistinct or indefinite. All bodies emitting purely calorific radiation, *i. e.*, radiation in which the energy is supplied by heat alone without infusion of electrical or chemical energy, follow Kirchhoff's law that the ratio of radiating and absorbing powers for a given wave-length and temperature is the same, and equal to the radiating power of the black body. Solids and liquids which can be heated to incandescence without complicating phenomena will generally be of this class. All bodies in which the energy radiated is supplied in whole or in part from other sources—chemical or electrical activity, for example—do not follow Kirchhoff's law. This kind of radiant energy is generally termed "luminescence" and bears no simple relation to the temperature. The radiation from gases is usually wholly or partly luminescent. E. Pringsheim,[2] in his paper

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[1] *Loc. cit.*

[2] *Rapports congrès international*, **2**, 100 *seq.*, 1900.

"L'émission des gaz," for the international congress at Paris (1900), distinguishes three kinds of radiation from gases:

(1) The phenomena which produce emission merely serve to bring the gas to the high temperature necessary for such emission. To this class the second law of thermodynamics is applicable; hence also Kirchhoff's law and the entire system of reasoning which has been reviewed.

(2) The electrical or chemical phenomena which produce the emission bring the gas into a somewhat modified state in which its radiating and absorbing powers differ with different initiating phenomena. Here Kirchhoff's law might be fulfilled in special cases.

(3) The electrical and chemical phenomena furnish entirely or partially the energy for the emission. Here the law of Kirchhoff finds no application.

If we now apply this analysis to solar radiation, and bear in mind that the surface layers in which the radiant energy for a temperature determination must originate are certainly gaseous, we see that the study of black radiation offers no royal road to the determination of the temperature of the Sun. It may yield a valuable approximation, but it is difficult even to determine just how valuable. Scheiner, almost alone among writers in this field, frankly acknowledges that our established generalizations upon black radiation are not properly applied to the determination of the temperature of the Sun, although he gives them in full and computes the solar temperature from them in various ways. He says:[1]

> On account of our lack of knowledge of the emitting power of the photosphere, a conclusion regarding its true temperature is not possible, and even if the emitting power were known, the real temperature would remain doubtful, since Stefan's law has been proved only for radiation from an absolutely black body.

The same analysis applies to the determination of terrestrial volcanic temperatures. We do not know the radiating power of the molten masses which now and then become exposed in volcanic openings, but the phenomena are or soon will be quite within the reach of laboratory research. In most cases the radiation is undoubtedly almost entirely calorific, and where this can be assumed with reasonable certainty, temperature estimates become correspondingly reliable, for the conditions of blackness are often remarkably well fulfilled in volcanic phenomena.

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[1] See *Strahlung und Temperatur der Sonne*, Leipzig, 1899, p. 50.

Let us now turn to the second difficulty in establishing a definite solar temperature. It is apparently a simple matter, but it is worth while asking[1] just what it means to say that the temperature of the Sun is 6000° or 8000° or 10000°. Temperature is not an additive function. We cannot take a number of bodies of the same temperature and by placing them in juxtaposition obtain a different temperature by summation as we lay a dozen foot-measures across a room and say the room is twelve feet long. We can obtain a measure of the temperature only through some phenomenon which varies with the temperature, and even then we must assure ourselves in some way that the phenomenon varies *uniformly* with equal increments of heat before we can make effective use of it. In the early researches the expansion of mercury was in most common use for this purpose, but it is of limited application and is not quite uniform in its expansion. Hydrogen was substituted after Lord Kelvin had shown that the expansion of a perfect gas would furnish an ideal temperature scale, but hydrogen is not an absolutely perfect gas. The international scale of temperature, as it is called, is now, by general agreement, based upon the expansion of hydrogen between the melting-point of ice and the boiling-point of water, divided into one hundred equal increments or degrees.

The measurement of the expansion of hydrogen has been continued up to six hundred such degrees,[2] but beyond this point no satisfactory containing vessel has been found for it. A less active and also less perfect gas — nitrogen — has been substituted, which has enabled the expansion measurements to be continued to 1150°.[1] The extension of the measurements upon hydrogen to 600° is proper extrapolation, and inasmuch as all gases approach the perfect gas at the higher temperatures, the continuation to 1150° with nitrogen may also be so regarded, but here trustworthy gas measurements end, and the extrapolated temperature scale on the basis of international definition ends also. The probability of its being continued upward for any considerable interval is small.

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[1] See also E. BUCKINGHAM, *Monthly Weather Review*, April 1903.

[2] P. CHAPPINS et J. A. HARKER, "Comparaison du thermomètre à résistance de platine avec le thermomètre à gaz, et détermination du point d'ébullition du soufre." *Travaux et mémoires du bureau international des poids et mesures*, **12**, 1-89; also *Phil. Trans.*, **194**, 37, 1900.

In choosing some other phenomenon which will vary with sensible uniformity as the temperature increases above this point, there is no limitation upon the selection except the convenience of the observer and the needs of his problem. To facilitate comparisons of results among widely separated scientists, it is desirable to retain the size of the unit or degree as nearly as possible, and one of the most common schemes is this: take a thermo-couple or element of suitable refractory metals (platinum with platinrhodium), inclose it in a furnace[2] with the bulb of the gas thermometer used above, and record the electromotive force at short intervals as far as the gas expansion can be measured. Then, *assuming* that the thermo-electric electromotive force will continue to increase in the ratio thus obtained, five hundred or more "degrees" above the highest point of the gas scale can be conveniently established. There is good reason to believe that these thermo-electric degrees agree well with the degrees of the gas scale, though in principle they form an independent system, merely numbered to conform to the generally adopted standard for the lower temperatures. This system of measurement also admits of but little extension beyond the present limit, unless more refractory thermo-electric materials can be found to replace the present ones.

Beyond this point (about 1600°) there is probably no better temperature phenomenon available for the purpose than the radiation from the black body which has just been considered. The comparison with the gas and thermo-electric scales over the long range from 0° to 1550° we have seen to be very satisfactory. And if the theoretical arguments which have been adduced in their support can be considered sufficiently conclusive, we have a radiation scale which will suffice for the highest temperature at which a black body can exist as such. So far as the authors are aware, but a single attempt has been made to do this, however, and only one temperature was established. Messrs. Lummer and Pringsheim[1] prepared a thin, hollow tube of carbon, surrounded it with an atmosphere of nitrogen, heated it electrically to a temperature corresponding to about 2000° C., and made three series of measurements of its temperature based upon three different formulæ for black radiation. The apparatus held out only through one short heating, but the three sets of results when reduced showed a maximum difference of only 1 per cent. (20°), although the temperature was almost twice as high as the nearest point on the gas scale (1150°). It was a splendid effort, and the excellent agreement of the three extrapolations among themselves goes far to establish the Stefan-Boltzmann law and the Wien displacement theorem as entirely general relations. A table of Lummer and Pringsheim's temperatures follows:

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[1] HOLBORN and DAY, *loc. cit.*, 1900.

[2] HOLBORN and DAY, *loc. cit.*

Method	T Absolute
Photometric	2310
Total radiation	2325
Photometric	2320
Total radiation	2330
Energy maximum	2330
Photometric	2330
Total radiation	2345
Energy maximum	2320

But if we take the Stefan-Boltzmann law, which undoubtedly rests upon the simplest and most secure fundamental reasoning of all the existing radiation equations, express its temperature relation in terms of the extended gas scale which reaches 1150°, assume it to be faultlessly supported by the thermo-electric extension to 1550° and by two other radiational formulæ in a single measurement at 2000°, and even assuming, further, that the Sun were an unquestioned black body, are we justified in saying that the temperature of the Sun, as determined from its radiation, is 6000° or 8000° or 10000° *upon the gas scale?* To extrapolate any well-established functional relation eight or ten times as far as it is supported by physical fact would require to be justified by very exceptional reasons or conditions, but to extrapolate one temperature phenomenon by a totally different one, so far into a domain inaccessible to all corroborative physical measurement, is quite meaningless. We have no temperature of 10000° in the sense in which we have a temperature of 1000°. If we are prepared, upon the basis of existing evidence, to consider the radiation scale established as a natural law, as has been proposed,[1] we might of course define all temperature in terms of it, including that of the Sun, if it could be shown to be a black body. These laws of radiant energy have unquestionably given us the best existing high-temperature scale—a scale which, in one most important particular, is a distinct advance over all other scales now in use: it is independent of the properties of any particular substance—but they are strictly confined to calorific radiation and are not properly used for the indefinite extrapolation of the gas scale.

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[1] O. LUMMER and E. PRINGSHEIM, "Die strahlungstheoretische Temperaturskala und ihre Verwirklichung bis 2300° abs.," *Vehr. Deutsch. Phys. Ges.*, (5) 1, 3, 1903.

There is another difficulty in the application of the laws of the black body to temperature measurement which is of a very practical character -calorific radiation is not usually black. In particular cases (lamp-black, platinum black) it approaches blackness, but all known substances possess limited properties of absorption and radiation, and cannot be reached directly until the law of distribution of energy in the spectrum of the black body is finally established. The error which arises in applying the Stefan-Boltzmann law to calorific radiation which is not black is best shown by citing the extreme case. Of all known refractory substances emitting pure temperature radiation, incandescent platinum reflects the largest percentage of the incident energy, and is therefore farthest removed from absolute blackness. Lummer and Pringsheim[2] have made a number of measurements upon platinum, a set of which ($T_{min.}$) is compared with similar measurements upon the black body ($T_{max.}$) in the table below:

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[1] O. LUMMER and E. PRINGSHEIM, *Vehr. d. Deutsch. Phys. Ges.*, (5)· **1**, 3-13, 1903.

[2] "Die Verteilung der Energie im Spektrum des schwarzen Korpers u. des blanken Platins," *Verh. d. Deutsch. Phys. Ges.*, **1**, 215-230, 1899.

	λ_m	$T_{max.}$	$T_{min.}$
Arc light......................	0.7 μ	4200° abs.	3750° abs.
Nernst lamp....................	1.2	2450	2200
Welsbach mantle..............	1.2	2450	2200
Incandescent lamp............	1.4	2100	1875
Candle.........................	1.5	1960	1750
Argand gas burner............	1.55	1900	1700

From these it appears that the maximum error can amount to 225° at 2000°, or about 10 per cent.—a quantity of inconsiderable magnitude compared with the differences in the earlier measurements of these quantities, and one which admits of correction in all particular cases. If a black body can be raised to the required temperature, or if the temperature be contained in an inclosed space which fairly fulfils Kirchhoff's conditions for blackness, excellent measurements of extremely high temperatures are possible. A very simple device for measuring much higher temperatures than have heretofore been accessible, and this without any form of contact between heated body and measuring apparatus, is due to Holborn and Kurlbaum,[1] and may be briefly described. A cheap telescope may be mounted with a tiny incandescent lamp in the focus of the object-glass and a monochromatic, transparent screen before the eyepiece. The lamp is fed with a measured current through an amperemeter and rheostat. Direct the telescope at a black body of known temperature (measured by bolometer or thermo-element) and vary the current in the lamp until it disappears against the black (perfectly absorbing, not necessarily black in color) background, and note the current. The disappearance is sharp and complete. Repeat the measurement for several temperatures and tabulate or plot them in terms of the current intensities. The temperatures of other bodies emitting calorific radiation can then be found by merely directing the telescope at them, regulating the current until the carbon filament disappears against the background, and noting the temperature which corresponds to the indicated current. One or two approximations are involved, and considerable refinements will suggest themselves in practice, but the remarkable simplicity of the apparatus, and the convenience with which completely inaccessible temperatures are measured, will serve to illustrate the possibilities of the radiation scale for an almost unlimited range of temperature measurement.

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[1] *Ann. d. Phys.*, **10**, 225-241, 1903.

Warburg,[1] in a recent paper before the Deutsche Physikalische Gesellschaft of Berlin, computes the solar temperature as follows: He assumes (1) that the rate of radiation per degree is constant, and (2) that the Stefan-Boltzmann law is applicable at all temperatures.

Let H_t = radiant energy corresponding to temperature t,
ϕ = apparent diameter of Sun = $0° 32'$,
s = solar constant,
h_1 = rate of radiation,
$= 0.0176 \dfrac{\text{gr. cal.}}{\text{cm}^2\,\text{sec.}}$ (Kurlbaum).

As a consequence of assumption (1), we have

$$\frac{s}{h_1} = \left[\frac{H_t - H_0}{H_1 - H_0}\right] \sin^2 \frac{\phi}{2} \,. \tag{1}$$

and from the Stefan-Boltzmann law,

$$\frac{H_t}{H_0} = \left[\frac{273 + t}{273}\right]^4 . \tag{2}$$

which substituted in (1) gives approximately

$$t = 273 \sqrt[4]{\frac{2.483}{\sin^2 \frac{\phi}{2}} \cdot \frac{s}{h_1}} - 273 \,.$$

From which, using the value of the solar constant obtained by

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[1] *Vern. Deutch. Phys. Ges.*, **1**, **2**, 50, 1899. See also SCHEINER, *Strahlung und Temperatur der Sonne*, Engelmann, Leipzig, 1890; and F. H. BIGELOW, "Eclipse Meteorology and Allied Problems," *Bul. I*, U. S. Dept. Agriculture, 1902.

Langley in his Mount Whitney observations[1] (14,898 feet elevation), 3.07 calories per sq. cm. per minute, $s = \frac{3.07}{60}$, and

$$t = 6286° \text{ C.}$$

Using his more recent tentative value[2] (which, by the way, he describes as probably somewhat too low), based upon observations near the sea level, $s = \frac{2.54}{60}$,
and

$$t = 5983° \text{ C.}$$

A series of very consistent determinations just published by Abbot[3] give a still lower value for the solar constant, $2.17 \frac{\text{cal.}}{\text{cm}^2}$.
Substituting this value, $s = \frac{2.17}{60}$
and

$$t = 5741° \text{ C.}^4$$

The second estimate is very simply made from the Wien law of the energy maximum:

$$\lambda_m T = 2940 \text{ (Lummer) and } \lambda_m = 0.49\mu \text{ (Abbot).}$$

Substituting these,

$$T = 6000° \text{ (abs.)} .$$

Paschen's[5] numerous determinations of this constant give 2921 as the mean value. Substituting

$$T = 5961° \text{ (abs.)} .$$

These assume that the Sun is a perfectly black body. Now the refractory substance farthest removed from the black body in its radiating properties, that is, the substance which reflects the largest percentage of radiant energy which falls upon it, is bright platinum. If the Sun is not a black body, but still is to be classed among purely calorific radiators, it must lie between the black body and platinum in its radiating properties. Considering the Sun to have only the radiating power of platinum, we should have, assuming Lummer's constant,

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[1] S. P. LANGLEY, "Researches on Solar Heat," Professional Papers of the Signal Service, No. 15.

[2] S. P. LANGLEY, "The Solar Constant and Related Problems," ASTROPHYSICAL JOURNAL, 17, 89–99, 1903.

[3] C. G. ABBOT, *Smithsonian Miscellaneous Collections*, 45, 74, 1903 (December 9).

[4] The Ångström value of the solar constant, 4 cal. per sq. cm, although probably more extensively quoted than any other, is undoubtedly much too high. (See ABBOT, *loc. cit.*).

[5] F. PASCHEN, "Ueber das Strahlungsgesetz des schwarzen Körpers," *Ann. d. Phys.* (4), 1, 277, 1901.

$$\lambda_m T = 2630 \text{ for platinum, and } \lambda_m = 0.49\mu \ ,$$
$$T = 5367^\circ \text{ (abs.)} \ ,$$

which may fairly be called the lower limit of possibility under the laws of radiant energy.

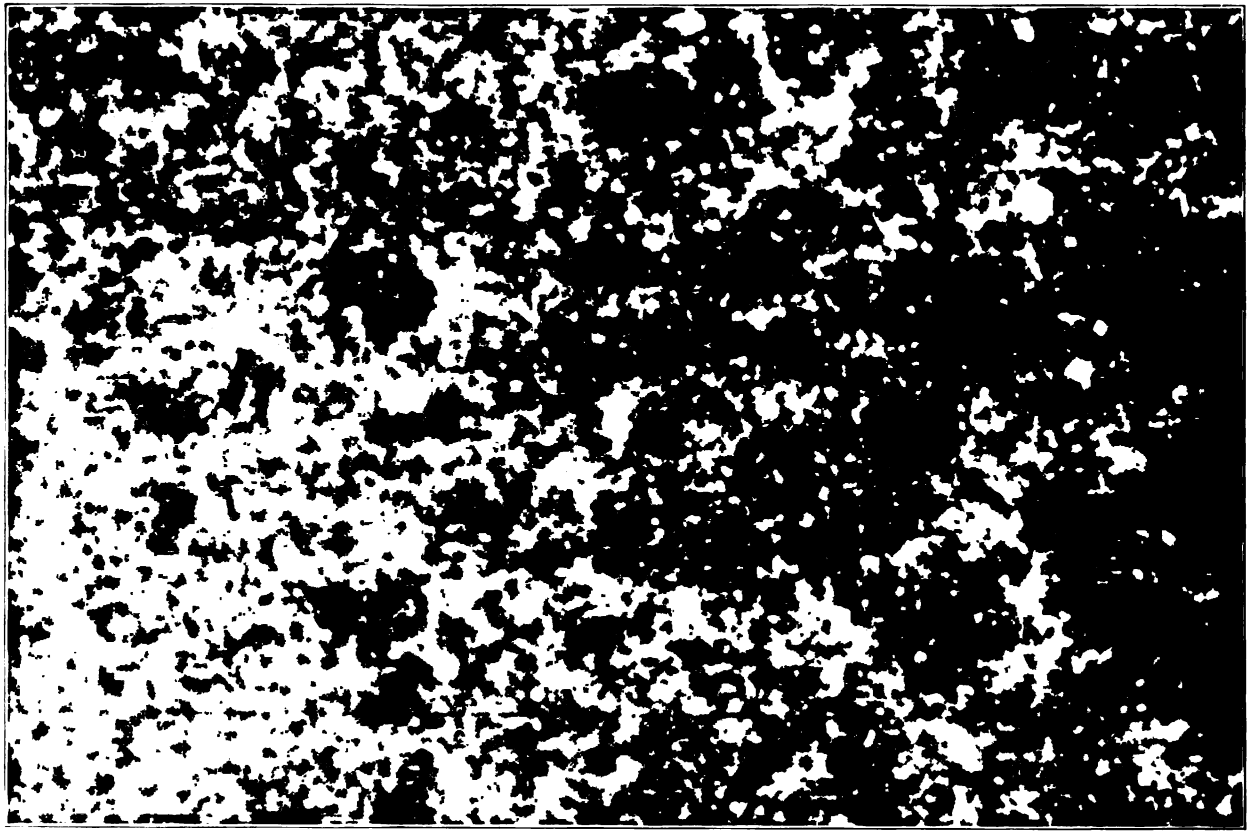
The last three temperatures are in terms of the absolute scale, and require to be diminished by 273° for expression in centigrade degrees. Taking all these values together, the laws of black radiation would appear to place the Sun at a temperature somewhat below 6000° C.

It is hardly fair to subject estimates of this character to such criticism as is usually applied to physical measurements, but it is plain that, assuming the validity of the established generalizations upon black bodies, they are applicable to the Sun, and that such extravagant extrapolation is justified by the inaccessible character of the Sun for such study, the differences in the values of the solar constant are still much too large.

It is noteworthy that as the limits of physical measurement have been extended, the estimates of the solar temperature have been gradually diminishing from 100000° and higher, until now we have a temperature almost within reach of terrestrial resources. The temperature of the electric arc is about 4000°, measured by the same methods.

U. S. Geological Survey,
Washington, D. C.,
November 1903.

PLATE II.



MINUTE STRUCTURE OF THE CALCIUM FLOCCULI AT H_2 LEVEL. 1903, SEPTEMBER 22.

(Scale: Sun's Diameter = 0.890 Meter.)

CALCIUM AND HYDROGEN FLOCCULI.

By GEORGE E. HALE and FERDINAND ELLERMAN.

. IN the ASTROPHYSICAL JOURNAL for November 1902 a brief account was given of the solar work then in progress at the Yerkes Observatory.[1] The paper contains a photograph of the Rumford spectroheliograph, but gives no detailed description of this instrument. Such a description has now been published as Part I, Volume III, of the *Publications of the Yerkes Observatory*. To this we may refer for details regarding the instrument and results; we propose to give here only a brief description of some of the results recently obtained, accompanied by reproductions of photographs from the paper in Volume III.

On account of the fact that the diameter of the solar image in the focal plane of the forty-inch refractor is more than three times as great as that of the image given by the twelve-inch Kenwood telescope, and also because of improvements in both the optical and mechanical construction of the Rumford spectroheliograph, the present results are much superior to those formerly obtained at the Kenwood Observatory. The Kenwood photographs show not only the larger regions of calcium vapor on the Sun's surface, but also those smaller elements that constitute a kind of reticulation, which covers the Sun from pole to pole. But the scale of the earlier photographs was quite insufficient to show the minute structure, resembling the granulation of the photosphere, which is clearly visible on all photographs taken under good atmospheric conditions with the Rumford spectroheliograph. Plate II, taken with the slit set at the center of the K line, shows this granulated appearance very clearly. It is also well shown in Fig. 2, Plate IV, where the size of the minute flocculi may be determined by the aid of the scale; but it does not appear to advantage in Plate I, on account of the comparatively large size of the squares in the half-tone screen. The question at once arises: What relation does this granulated structure bear to that of the photosphere? More specifically, are the small luminous masses of calcium vapor to be regarded as roughly spherical in form, in accordance with Janssen's view of the structure of the grains of the photosphere, or are they to be considered as the summits of columns of calcium vapor, rising from the upper portion of those columns of condensed vapors which, in Langley's view, produce the well-known photospheric granulation?

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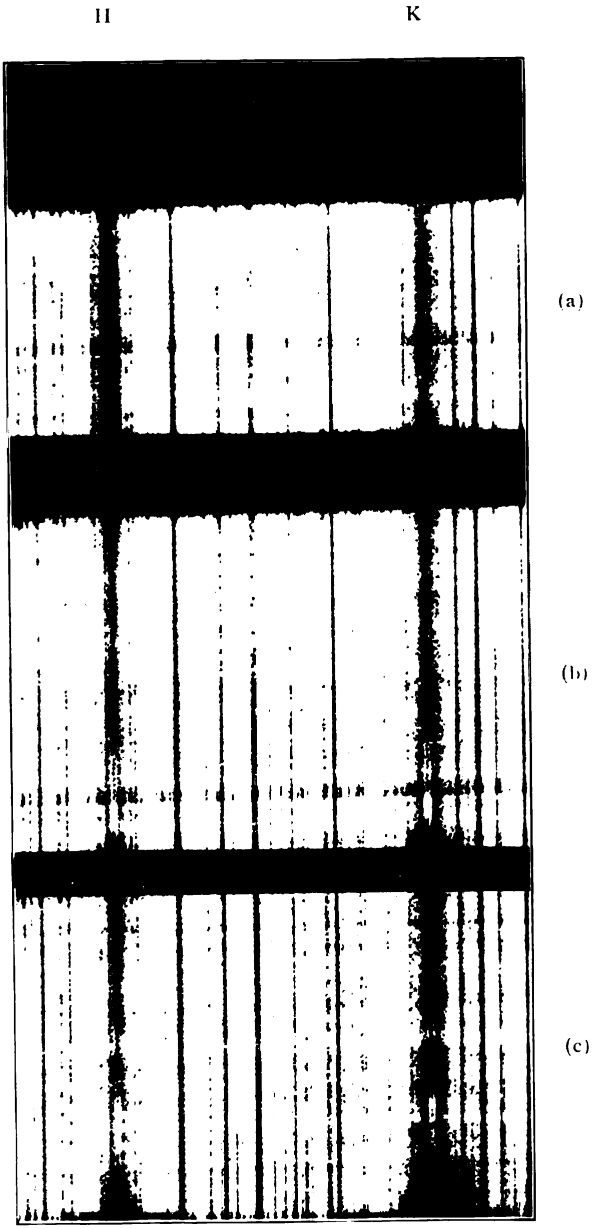
[1] GEORGE E. HALE, "Solar Research at the Yerkes Observatory," ASTROPHYSICAL JOURNAL, November, 1902.

At this point it should be remarked that the name "faculæ," formerly employed by one of us to designate the calcium clouds photographed with the spectroheliograph, is no longer to be regarded as suitable. Indeed, this fact was long ago pointed out by Deslandres. But in the earlier stages of the work it did not seem desirable to introduce a new term, especially as the calcium regions are closely related with the faculæ, and frequently are exactly similar to them in form. Nevertheless, the calcium vapor, as is clearly shown by the results given in this paper, occupies a region higher above the photosphere than that occupied by the faculæ. It has now seemed best, in order to avoid any possible confusion in the future, to suggest the name *flocculus* to distinguish a mass of vapor from the facula which may or may not lie below it. The *faculæ*, then, are elevated regions of the photosphere, which may be seen with the eye and on direct photographs when not too near the center of the Sun, and which are characterized by a continuous spectrum. The *flocculi* are clouds of gas or vapor lying at a higher level, which are not visible in direct observations or in ordinary photographs, but are shown on photographs taken with the spectroheliograph. The term "flocculi" is applied indiscriminately to all bright or dark clouds of vapor photographed in projection on the Sun's disk, without distinction of level. In other words, a flocculus may be a mass of vapor in the reversing layer, or in the chromosphere, or in a prominence. As will be shown in this paper, the forms of the clouds of calcium, hydrogen and other vapors photographed in projection on the Sun's disk are not always the same. For this reason we shall speak of calcium flocculi, hydro-

PLATE III.



H and K Lines on the Disk, in the Chromosphere, and in a Prominence (a).

PLATE IV.

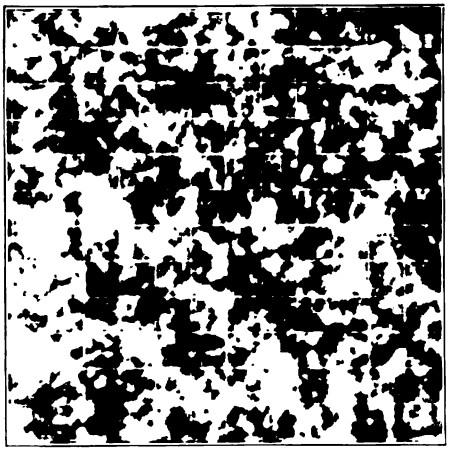


FIG. 2.—Minute Calcium Flocculi (H_2). The Squares are 10″ on a Side.

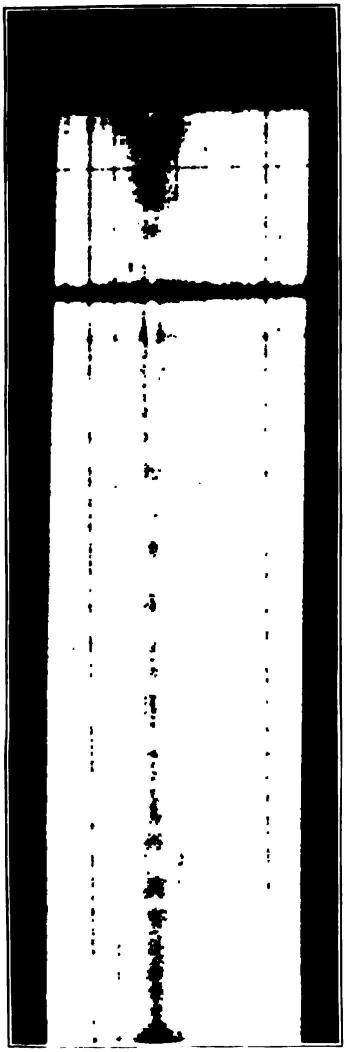


FIG. 1.—K Line on the Disk and at the Limb.

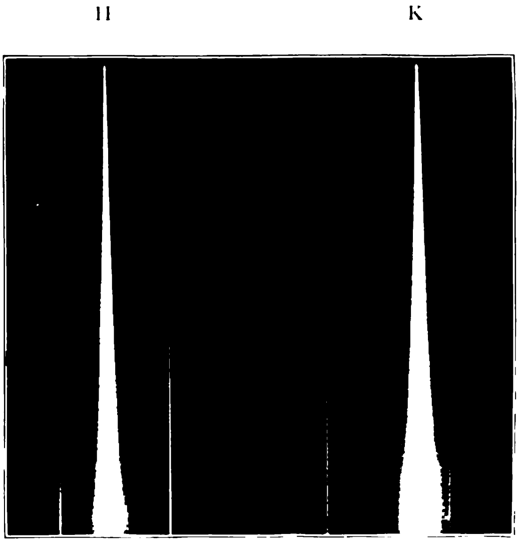


FIG. 3. H and K Lines in Electric Arc Showing Reversals.

gen flocculi, etc. The method of determining the level represented by a given photograph is described below.

FORM OF THE CALCIUM FLOCCULI AT DIFFERENT LEVELS ABOVE THE PHOTOSPHERE.

In order to determine the nature of the calcium flocculi, it is evident that great advantage would result from the use of a method which would permit sections of the columns of calcium vapor, if such exist, to be photographed at different heights above the photosphere. It is fortunately possible to accomplish this result by the use of a method which appears to have received no previous practical application in the solution of this question, though it was described in an article published in the *Comptes Rendus* by Deslandres in 1894. Deslandres points out in this paper that photographs taken with the second slit of a spectroheliograph set on the broad dark shade of the K line ought to give results different from those obtained when the slit is set on the bright line at the center of K. But he does not refer to the fact that different results will be obtained when the second slit is set at different points on the broad dark shade.

In order to make the matter clear, let us consider Fig. 3, Plate IV, which is reproduced from a photograph of the H and K lines in the spectrum of the electric arc. At the center of the arc, corresponding to the lower part of the photograph, the calcium vapor is dense and the lines are very broad. In the outer part of the arc, corresponding to the upper part of the photograph, the calcium vapor is comparatively rare, and the lines are narrow. The breadth of the lines in the intermediate regions varies with the density of the calcium vapor. The fine dark line of reversal through the center of the lines is produced by the cool, rare calcium vapor in the extreme outer part of the arc.

A similar condition of things exists in the Sun. As will be seen by reference to Plate III and to Fig. 1, Plate IV, we have at H and K in the spectrum of the Sun's disk a composite structure, composed of three parts: (1) a broad, dark band, which we shall designate as H_1 or K_1; (2) a comparatively narrow bright line, lying at the center of this band, at points on the Sun's disk where the slit crosses hot masses of calcium vapor (H_2, K_2); and (3) a very narrow dark line running through the center of H_2 and K_2 (H_3, K_3). The diffuse dark bands H_1, K_1 are due to the comparatively dense calcium vapor which lies near the photosphere. In general, as we know from eclipse results and from our own photographs of the spectrum of the chromosphere taken in full sunlight with a tangential slit, the dense vapor corresponding to H_1, K_1 lies so low in the chromosphere that it cannot be observed projecting above the Sun's limb. In photographs of the spectrum of the chromosphere taken with radial slit, H_2 and K_2 are seen to project for some distance above the Sun's limb, though they do not extend to the highest part of the chromosphere. In this region, where the calcium vapor is less dense, the lines narrow down so as to give the well-known "arrow-head" appearance; in the upper chromosphere and in prominences they are very narrow, and since the vapor is cooler at these elevations, a narrow dark absorption line (H_3, K_3) is produced at the center of H_2 and K_2.

We are not prepared to explain why H_2 and K_2 appear as bright lines, acting as though the intermediate mass of vapor to which they correspond were hotter than the vapor above and below it. It may be that some electrical or chemical effect is responsible for this appearance, and it would therefore be unsafe to assume that an abnormally high temperature prevails in this intermediate layer.

It is evident that if the second slit of the spectroheliograph is made to correspond with the extreme outer edge of H_1 or K_1, it can receive light only from that calcium vapor which is dense enough to produce a line of this breadth. The rarer vapors, at higher levels, produce narrower lines, which therefore send no light through the second slit. When the slit is set nearer the center of the line it receives light from the vapor at higher levels, and also, of course, from the vapor at lower levels. But as the intensity of radiation of the vapor increases with increasing height above the photosphere, up to the H_2, K_2 level, the successive photographs will in general tend to show sections of the

PLATE V.

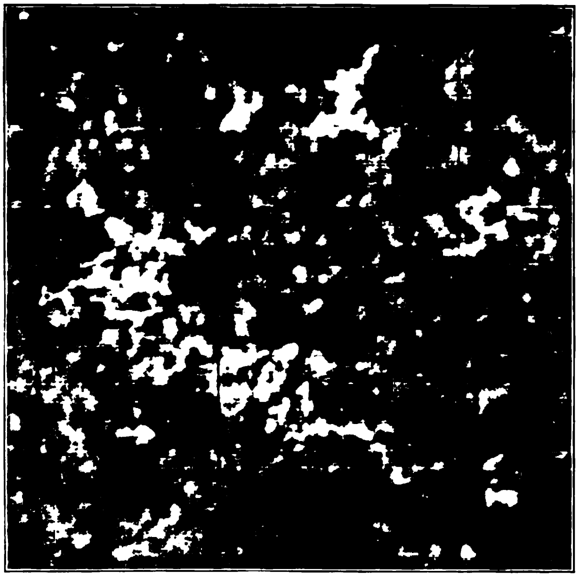


Fig. 1.—3^h 40^m. Low H_1 Level. Slit at λ3962.

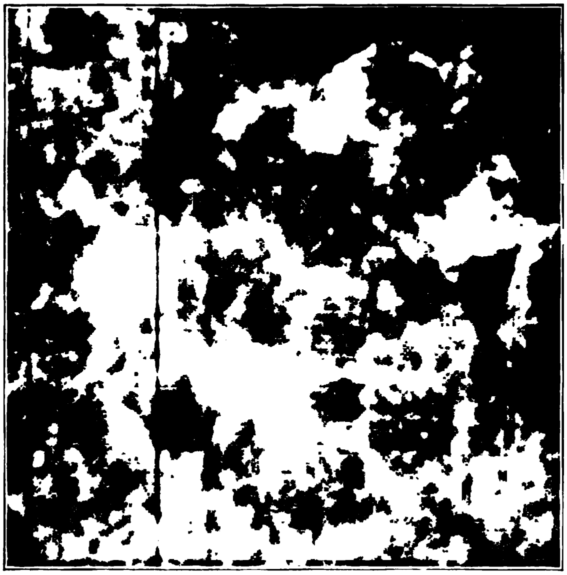


Fig. 2.—3^h 31^m. H Level. Slit at λ3968.6. Same Region as Fig. 1.

Minute Structure of the Calcium Flocculi,
1903, September 22.
(Scale: Sun's Diameter = 0.800 Meter.)

calcium clouds, corresponding to the highest level at which the vapor is dense enough to produce a line sufficiently wide to enter the second slit. It is evident that the cooler vapor of the H_3, K_3 level would not in general be shown in photographs taken with a second slit wide enough to include the whole of the H_2, K_2 line. But in some cases, because of greatly increased width and intensity of H_3, K_3, and the faintness or absence of H_2, K_2, the absorbing vapors of the highest level should be shown.

An examination of the photographs reproduced in Figs. 1 and 2, Plate V, will show how this method has been used to determine the structure of the calcium flocculi. It will be seen that the low-level photograph (Fig. 1) shows a series of comparatively small and well-defined elements at the base of the flocculi, which at the higher level of Fig. 2 expand, and probably overhang, so as to cover a much larger area. From this and other results, obtained under the very perfect atmospheric conditions essential in a case of this kind, it seems probable that the calcium flocculi are in general made up of a series of columns, which expand as they reach higher levels, and in many cases overhang laterally. Before this question can be finally solved, however, it will be necessary to secure a large number of photographs under very perfect atmospheric conditions.

Plates VI and VII will serve to illustrate the method of photographing sections corresponding to different levels. The two photographs of the great Sun-spot of October 1903, which are especially arranged in Plate VIII for purposes of comparison, will serve to give a still better illustration of the method. The high-level photographs in Plates VII and VIII seem to give definite indications of the presence of dark regions, not shown in the low-level photographs, which are not improbably caused by the absorption of cooler vapors at higher levels.

HYDROGEN FLOCCULI.

In employing the spectroheliograph to photograph the Sun's disk through dark lines other than H and K, it is obvious that the principal condition to be fulfilled is that the linear dispersion shall be sufficient to cause the line in question to be wider than the second slit. If this is not done, it is evident that light from the continuous spectrum on either side of the dark line will reach the photographic plate, and that very little of such light would be sufficient completely to annul the effect produced by variations in intensity of the dark line. For while the dark lines are, of course, dark only by contrast, their light is much less intense than that of the continuous spectrum on which they lie.

A most valuable property of the spectroheliograph, which has not hitherto received special attention, is its power of recording bright or dark regions whose intensity differs so little from that of the general solar surface that the existence of such regions would never be suspected from photographs of spectra alone. The sensitiveness of the instrument in this regard seems to be due to the well-known physiological fact that although differences in intensity of the various parts of a narrow line might not be perceptible, they would become so if the line were greatly widened. Through this property of the spectroheliograph, it becomes possible to photograph hydrogen and metallic flocculi not previously recognized with the spectroscope or by other methods of observation.

In May of the present year the Rumford spectroheliograph was so modified as to render it available for photography with some of the wider dark lines, notably those of hydrogen. The optical train of the instrument, as ordinarily used with the H and K lines, consists of a plane mirror, which reflects the parallel rays coming from the collimator lens to the first of two 60° prisms of light flint glass (Fig. 1). The total deviation of the ray employed, after refraction by the prisms, is 180°. For work with the dark lines we decided, after some experimenting, to substitute a plane grating ruled with 20,000 lines to the inch for the mirror of the above combination. The position of the grating is such as to cause any desired region in the first-order spectrum to fall on the first prism, after which it is further dispersed by the two prisms of the train. The advantage of this combination is not only to give greatly increased dispersion, but also to reduce very materially the diffuse light of the grating,

PLATE VI.

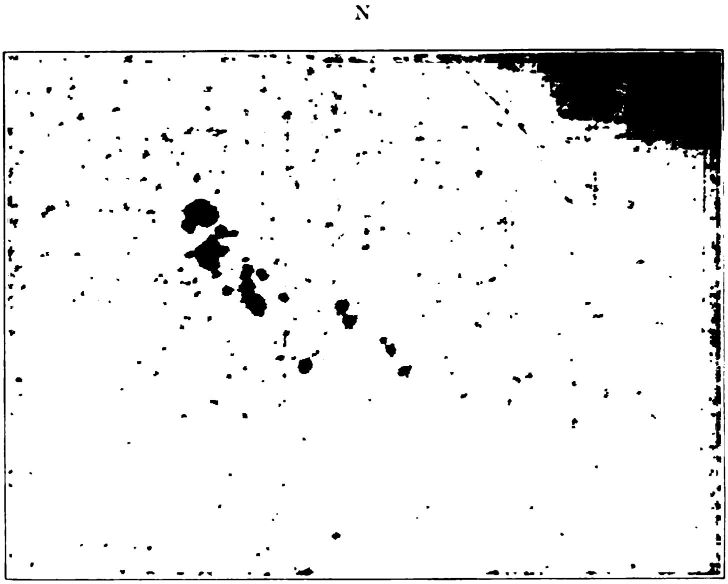


FIG. 1. 11h 32m. Faculæ. Slit on Continuous Spectrum at λ 3924.

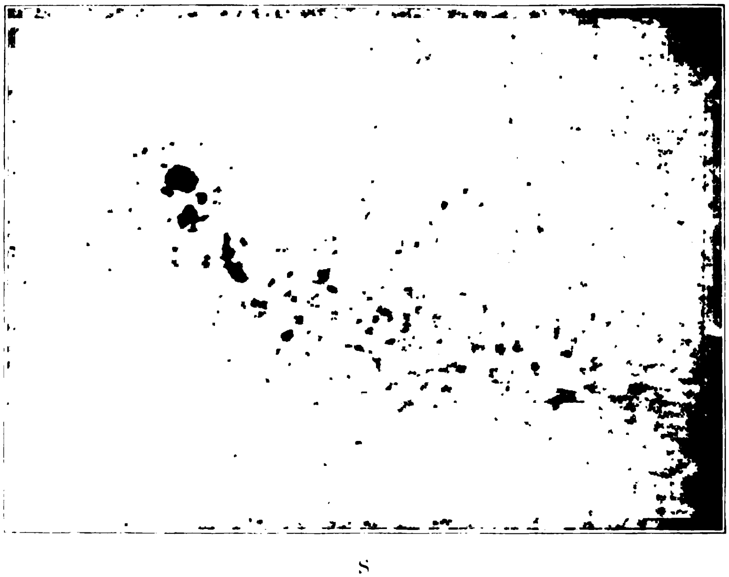


FIG. 2. 11h 22m. Calcium Flocculi, Low K_1 Level. Slit at λ 3929.

FACULÆ AND LOW-LEVEL SECTION OF CALCIUM FLOCCULI, 1903, APRIL 29.
(Scale: Sun's Diameter = 0.280 Meter.)

PLATE VII.

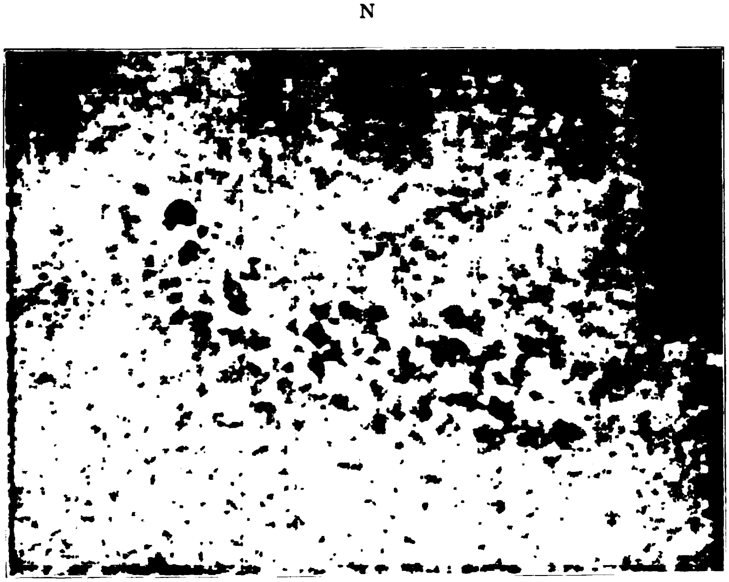


FIG. 1.—$10^h\ 28^m$. Calcium Flocculi, Higher K_1 Level. Slit at λ 3932.

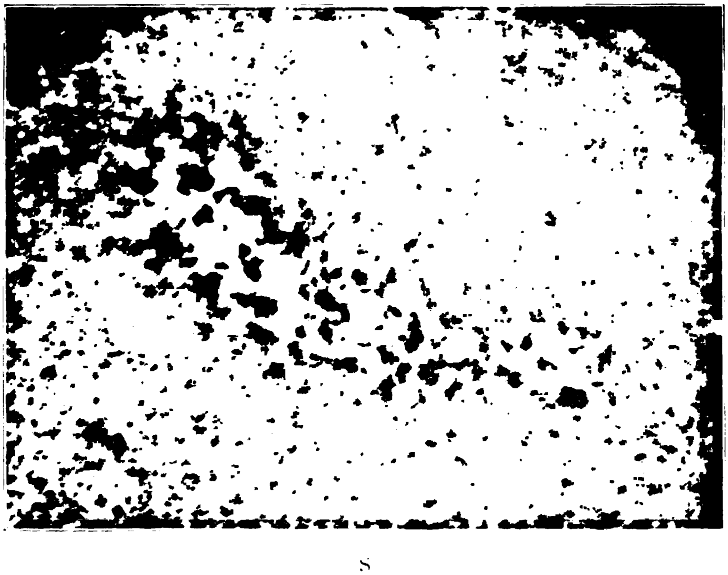


FIG. 2.—$11^h\ 11^m$. Calcium Flocculi, K_2 Level. Slit at λ 3933.8.

SECTIONS OF CALCIUM FLOCCULI AT DIFFERENT LEVELS, 1903, APRIL 29.
(Scale : Sun's Diameter 0.280 Meter.)

which would seriously affect the photographs if not dispersed by the prisms before reaching the sensitive plate.

On developing the first plate made with the $H\beta$ line, we were surprised to find extensive *dark* regions, scattered over the surface of the Sun, and resembling in form the bright flocculi obtained with the H or K lines. On careful examination it was found that while the dark regions of hydrogen resembled in a general way the bright regions of calcium, nevertheless there was a marked difference in form in many instances, and almost never an exact agreement. The results given by this plate were confirmed by subsequent photographs, leaving no doubt that the hydrogen flocculi are, in general, dark, and that while they have a general resemblance in form to the bright calcium flocculi, the differences are in many cases very striking.

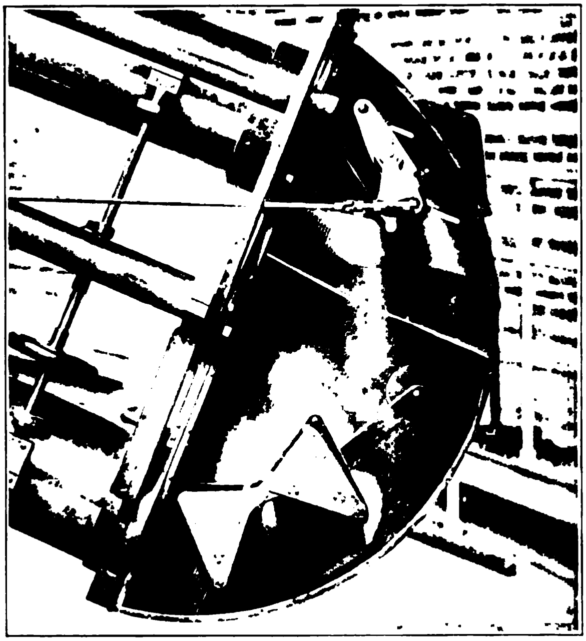


FIG. 1. -Prism-Box.

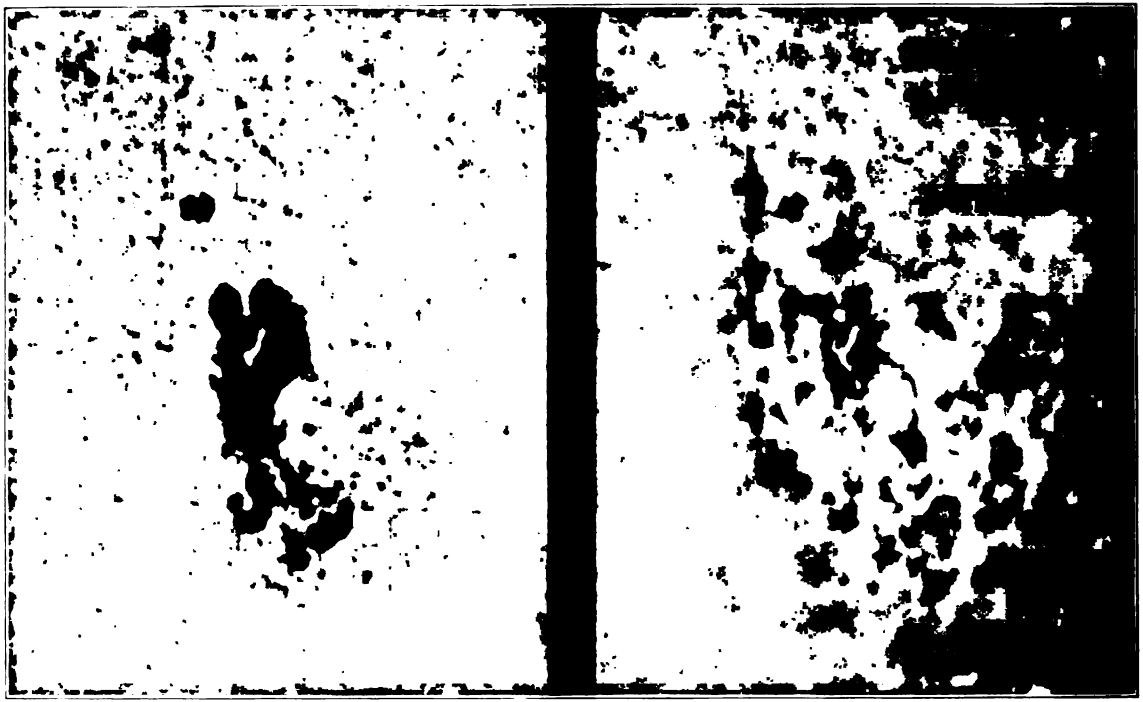
We soon found, as was expected from visual observations, that in the vicinity of active Sun-spots, and, in general, in regions of considerable activity, *bright* hydrogen flocculi often appear. While these are frequently eruptive in character, they are not always so. The temperature of the hydrogen gas (or whatever factor determines its radiating power) is apparently so near the neutral point that in some regions a flocculus may be dark, whereas, in an adjoining region, through superabundance of radiation, the flocculus may appear bright. Under such circumstances it is evident that the hydrogen which is exactly at the neutral point will not appear on the photographs. The hydrogen that does appear is shown because its radiating power is greater or less than that of the surrounding hydrogen gas. Plates IX to XII permit a comparison to be made between dark hydrogen flocculi and bright calcium flocculi, although in all cases the time interval is too great to make an accurate comparison of form of any value. In Fig. 2, Plate IX, it will be noticed that the flocculus is bright immediately about the spot, and dark at greater distances away. In Fig. 2, Plate X, small bright flocculi, indicative of eruptive phenomena, may be seen to the west of the spot. A more striking contrast is afforded by Plates XI and XII, which show the surroundings of the great Sun-spot of October 1903, as photographed with the calcium and hydrogen lines.

Photographs of the hydrogen flocculi have been made with the $H\beta$, $H\gamma$, and $H\delta$ lines. They are now taken as often as possible with the Rumford spectroheliograph, for systematic study in conjunction with the calcium photographs.

DARK CALCIUM FLOCCULI.

The discovery of the dark hydrogen flocculi led us to make a careful examination of our plates in the hope of finding conclusive evidence of the existence of *dark* calcium flocculi. We have found a number of cases, which seem to leave no doubt as to the reality of the phenomena. One of these is illustrated in Fig. 1, Plate XIII; the corresponding dark hydrogen flocculus is given for comparison (Fig. 2). It was through the exceptional intensity of this hydrogen flocculus that the dark calcium flocculus was found.

PLATE VIII.



October 9, 3^h 43^m. Calcium Flocculi, Middle H_1 Level.
Slit at λ 3966.

October 9, 3^h 30^m. Calcium Flocculi, H_2 Level.
Slit at λ 3968.6.

THE GREAT SUN-SPOT OF OCTOBER 1903.
For Comparison with the Stereoscope.

PLATE IX.

N

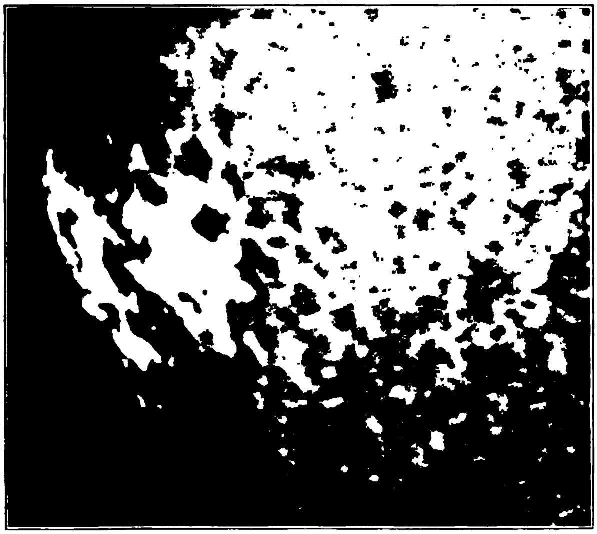
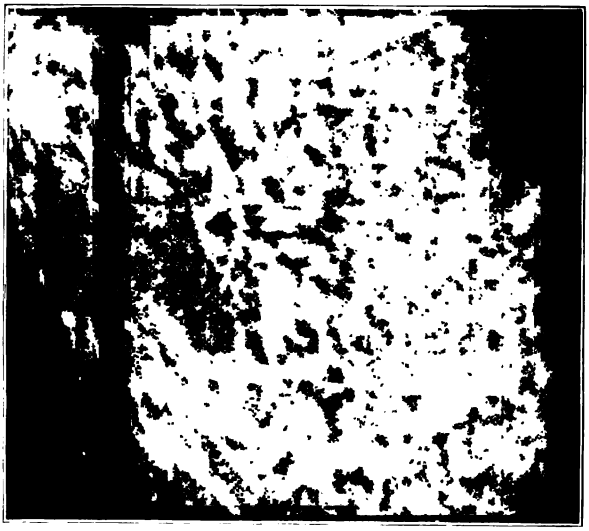


FIG. 1.—July 2, $9^h\ 39^m$. Calcium Flocculi, K_2 Level.
Slit at $\lambda\,3933.8$.

E W



S

FIG. 2. July 2, $3^h\ 40^m$. Hydrogen Flocculi.
Slit at Center of $H\beta$.

COMPARISON OF CALCIUM AND HYDROGEN FLOCCULI.

(Scale: Sun's Diameter = 0.335 Meter.)

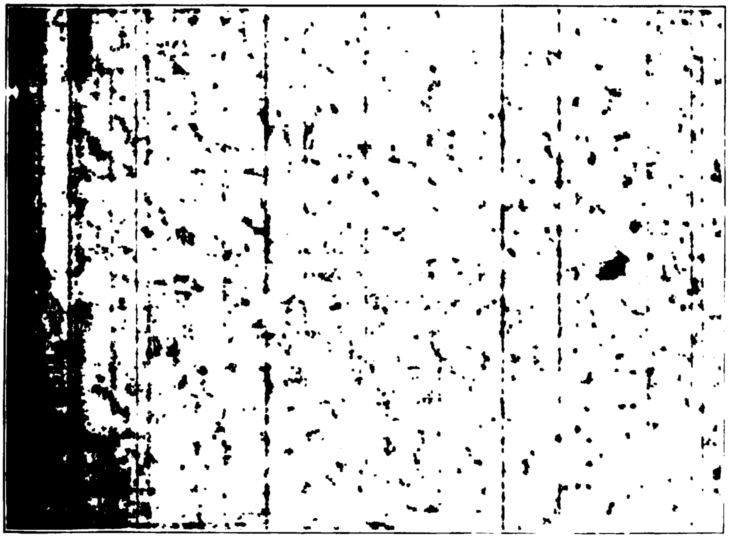
PLATE X.

N

Fig. 1.—3^h 57^m. Calcium Flocculi, K_2 Level. Slit at λ 3933.8.

E

W



S

Fig. 2.—11^h 0^m. Hydrogen Flocculi. Slit at Center of $H\gamma$. (Bright Eruptive Flocculi West of Spot.)

Hydrogen and Calcium Flocculi, 1903, July 7.

(Scale: Sun's Diameter = 0.290 Meter.)

FUTURE WORK.

The preliminary results here given will suffice to suggest the general character of the work which may be expected from the spectroheliograph in the future. If advances are to be made far beyond the point attained by the present work, it is evident that two conditions should be fulfilled: (1) Provision should be made for the use of spectroheliographs having much higher dispersion, so that some of the narrower dark lines may be employed. (2) Much advantage should be derived from the use of still larger solar images, especially at sites where the atmospheric conditions are particularly favorable. Unless the best seeing is available, it will be impossible to photograph the finest details of the solar surface. With a sufficiently large solar image, good seeing, and very high linear dispersion, it should become possible to make photographs showing the distribution of the vapors corresponding to the widened lines and the bright lines in Sunspots. Such work should be of great importance, if carried on in conjunction with the study of the spectra of Sun-spots, made with instruments of high dispersion.

A report on the instrumental and atmospheric conditions required in future work on the Sun may be found in the forthcoming *Year Book* (No. 2) of the Carnegie Institution.

YERKES OBSERVATORY,
December 1903.

DESCRIPTION OF THE PLATES.

PLATE I.

Entire disk of Sun, as photographed 1903, August 12, 8^h 52^m C. S. T. with the H_2 line. Same size as original negative. The squares of the half-tone screen are too coarse to permit the smallest details to be shown.

PLATE II.

Minute calcium flocculi, H_2 level, showing their normal appearance under excellent conditions of seeing.

PLATE III.

H and K lines on the solar disk and in the chromosphere (radial slit). *a* shows H_3 and K_3 (very faintly) in a prominence.

PLATE IV.

FIG. 1.—The K line on the solar disk and in the chromosphere at the limb (radial slit). The bright reversals (K_2) are due to the flocculi. Where faculæ are present the continuous spectrum is more or less strengthened.

FIG. 2.—Minute calcium flocculi, resembling the granulation of the photosphere. The squares are 10″ of arc on a side.

FIG. 3.—Reversals of the H and K lines in the electric arc, showing the decrease in width from the inner (dense) to the outer (rare) calcium vapor.

PLATE V.

FIG. 1.—Low-level (H_1) section of calcium flocculi, showing how these flocculi appear to be made up of vertical columns of calcium vapor.

FIG. 2.—High-level (H_2) section of the same flocculi, showing (faintly) how the vapor columns seem to be bent over at the summit, as well as expanded.

PLATE VI.

FIG. 1.—For this photograph the second slit was set on the continuous spectrum at λ3924. Consequently no flocculi are shown, though the faculæ are faintly visible. The forms of the latter should be compared with those of the flocculi in Fig. 2.

FIG. 2.—Low K_1 level. Slit set at λ3929. This shows the dense calcium vapor not far above the photosphere. Compare with Fig. 1, and note that even at this low level the calcium vapor overhangs, and sometimes completely covers small spots.

PLATE VII.

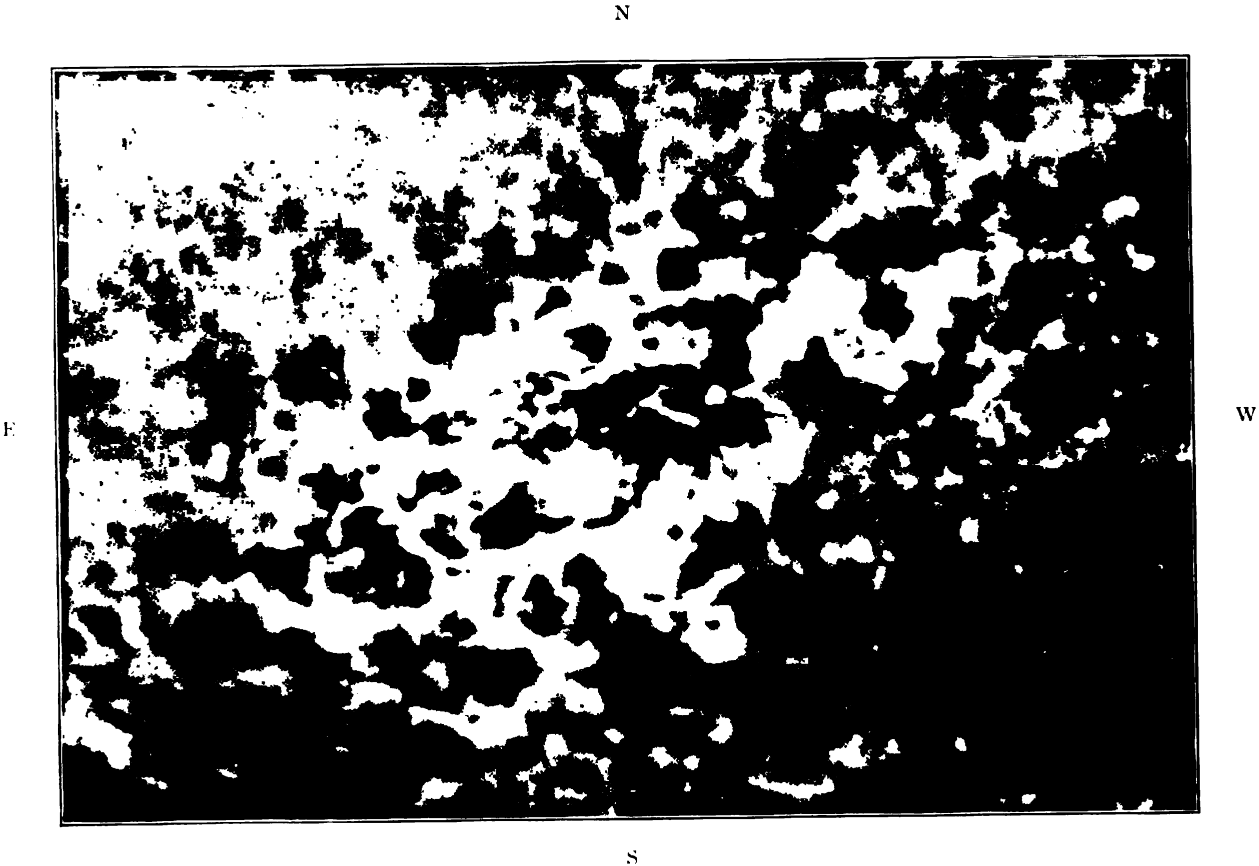
FIG. 1.—Higher K_1 level. Slit at λ3932. Though taken before the photographs reproduced in Figs. 1 and 2 of Plate VI, this picture further emphasizes the differences noted at lower levels. The fact that the changes are progressive largely eliminates the time element, which might otherwise be suspected of causing the observed differences. As a matter of fact, these flocculi are quiescent and slowly changing, differing very decidedly from eruptive phenomena.

FIG. 2.—K_2 level. Slit at λ3933.8. Here the calcium vapor is very brilliant, and covers a larger area. The photograph contains distinct evidence of dark absorbing masses at higher levels. Perhaps the best instance of this is the dark tongue which runs somewhat north of west from the small spot south preceding the largest one of the group. This tongue seems to form a part of an extensive dark area, which completely surrounds the bright flocculi of the group.

PLATE VIII.

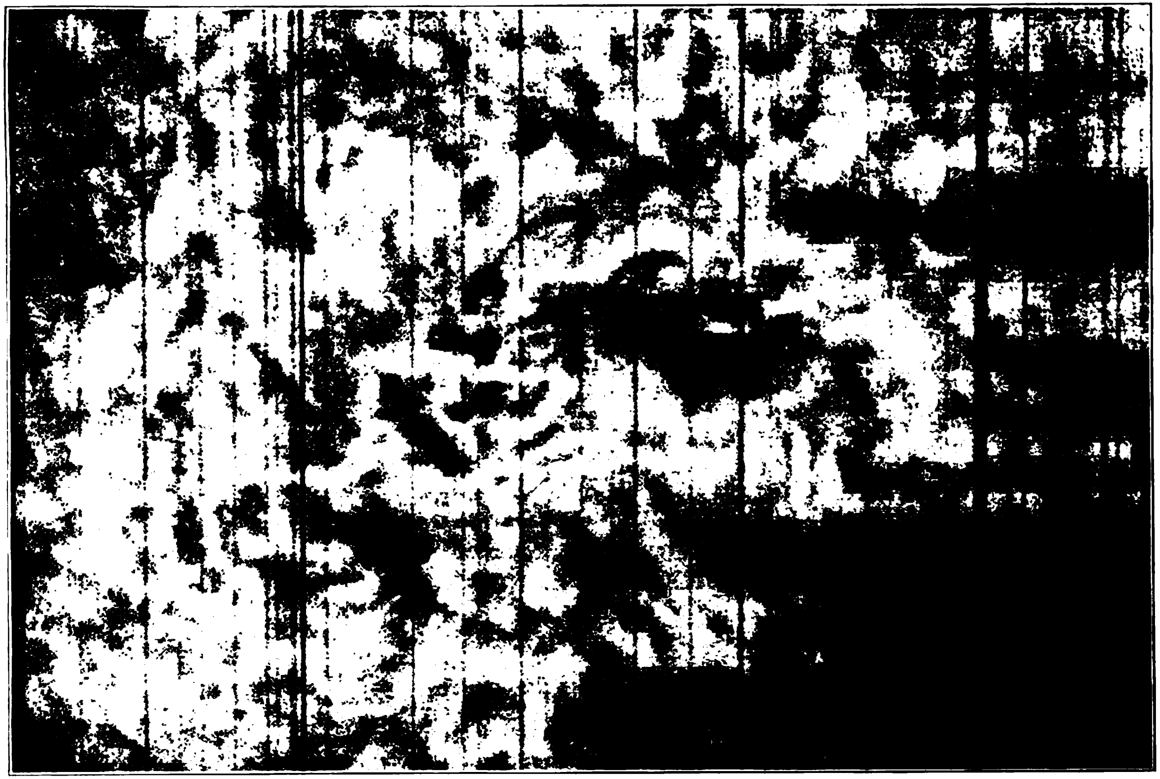
In comparing the photographs corresponding to different levels a double stereopticon is used, by which two negatives can be projected upon a screen, where the images are exactly superposed. The method has proved so instructive that it has seemed desirable to provide with this paper a simple

PLATE XI.



October 9, $3^h\ 30^m$. Calcium Flocculi, H_2 Level.
THE GREAT SUN-SPOT OF OCTOBER 1903.
(Scale: Sun's Diameter = 0.550 Meter.)

PLATE XII



October 9. $1^h\ 04^m$. Hydrogen Flocculi.

THE GREAT SUN-SPOT OF OCTOBER 1903

(Scale: Sun's Diameter = 0.550 Meter.)

means of accomplishing the same result. Accordingly, a pair of high- and low-level photographs has been arranged for use with the stereoscope. It is to be understood that no stereoscopic effect in the ordinary sense will be obtained in examining these photographs. The purpose of using the stereoscope is merely to allow the images to be superposed, thus permitting them to be seen at the same point in rapid succession by quickly moving a card so as to cover alternately the two lenses of the stereoscope. In this way the same region of the Sun may be examined, first as it appears at the low level of the denser calcium vapor, and then as it appears at the higher level of the rarer vapor. Thus the manner in which the calcium flocculi overhang the penumbra, and sometimes the umbra of spots, and the absence at the lower level of the dark structures shown in certain parts of the high-level picture, can be observed. This method of comparison also gives an excellent means of detecting small changes in the form of the flocculi, as shown by photographs corresponding to the same level, but taken at different times.

PLATE IX.

FIG. 1.—Calcium flocculi surrounding a spot when near the east limb of the Sun. The strong dark regions in this photograph are due to too great contrast in the original photograph, and not to dark calcium flocculi.

FIG. 2.—The same region about six hours later, as photographed with the $H\beta$ line. Near the spot the hydrogen immediately surrounding the spot appears to be bright, while an extensive dark hydrogen flocculus lies to the east, occupying approximately the same region as that of the bright calcium flocculus.

PLATE X.

FIG. 1.—The contrast here is rather too great, and for this reason the background appears too dark. The general character of the bright calcium flocculi is nevertheless fairly well shown.

FIG. 2.—The contrast in this photograph is more nearly what it should be, though the background is in general too bright. Some well-defined examples of bright hydrogen flocculi may be seen to the west of the spot, where small spots were developing at the time.

PLATE XI.

At this level the penumbra is almost completely covered by the flocculi, while many of the smaller spots are blotted out. There are also distinct evidences of dark flocculi, due to absorbing vapors at still higher levels. The illustration necessarily fails to indicate the brilliancy of the brightest eruptive phenomena, which on the original negative are easily distinguished from the ordinary flocculi.

PLATE XII.

This photograph, which shows the hydrogen flocculi surrounding the spot group, should be compared with Plate XI. The brighter regions are in most cases eruptive. In general the hydrogen flocculi in the less disturbed regions are dark, though they may perhaps be bright or neutral where they overhang the penumbra, and cover some of the smaller spots of the group.

PLATE XIII.

FIG. 1.—Dark calcium flocculus, corresponding to the exceptionally dark hydrogen flocculus shown in Fig. 2, which represents the same region of the Sun. The contrast in Fig. 1 is rather too great, and some regions which might seem to resemble dark flocculi should appear much lighter.

FIG. 2.—Exceptionally strong dark hydrogen flocculus. Compare with Fig. 1.

It should be noted that all the photographs of hydrogen flocculi are slightly distorted, owing to the fact that a straight first slit and a curved second slit are used with the grating.

PLATE XIII.

N

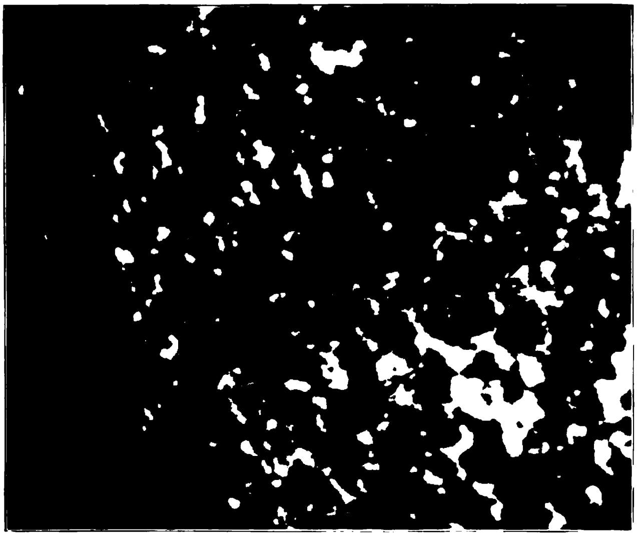
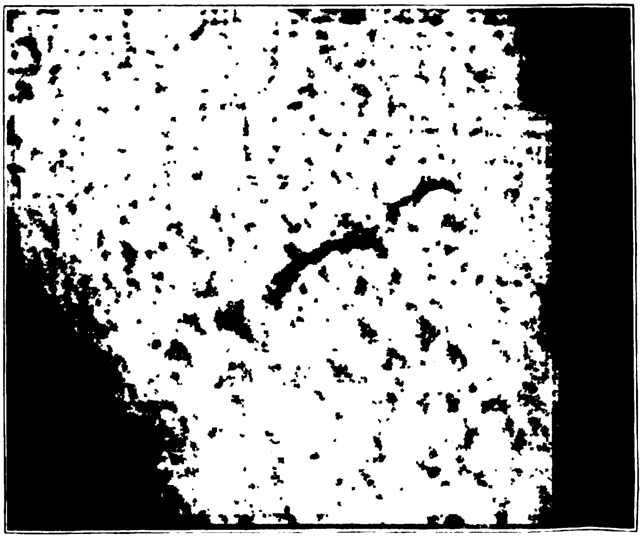


FIG. 1.—June 17, 9^h 08^m. Dark Calcium Flocculus. Slit at λ 3933.8.

E

W



S

FIG. 2.—June 17, 10^h 18^m. Strong Hydrogen Flocculus.
Slit at Center of *Hβ*. (Compare with Fig. 1.)

COMPARISON OF DARK CALCIUM AND HYDROGEN FLOCCULI.
(Scale: Sun's Diameter = 0.350 Meter.)

ON METHODS OF TESTING OPTICAL MIRRORS DURING CONSTRUCTION.

By G. W. RITCHEY.

NO GREATER mistake could be made than to assume that cheap and poorly annealed disks of glass, or those with large striæ or pouring marks, are good enough for mirrors of reflecting telescopes. While I am not prepared to say that optical glass of the finest quality must be used for mirrors to secure the best attainable results, it is evident that a high degree of homogeneity and freedom from strain is necessary in order that the figure of a mirror shall not be injuriously affected by temperature changes. If it were not necessary to consider the question of cost, I should advise the use of the finest optical (crown) glass for mirrors, in order to be as free as possible from risk. Usually considerations of expense would, in the case of large mirrors, make it necessary to chose between an optical disk of a given size, and a somewhat larger one of the kind furnished by the St. Gobain Company, for example. The diagonal plane mirror for a Newtonian, and the convex mirror of the Cassegrain reflector, should always be made of the best optical glass, since the expense for these is comparatively slight.

A very important point is in regard to the necessary thickness of the glass disks. As a result of experience with many mirrors of from six to sixty inches diameter, in which the thickness of the several disks varies from one-twelfth to one-sixth of the diameter, I have no doubt that the thicker disks are always preferable, provided that they are as homogeneous and as well annealed as the thinner ones. The thinner mirrors suffer much greater temporary change of curvature from the very slight heat generated during the process of polishing, and they undoubtedly suffer greater temporary disturbance of figure from changes of temperature when in use in the telescope. In the case of the large paraboloidal mirror of a reflecting telescope, which should always be properly supported at the back to prevent flexure, the thickness should be not less than one-eighth or one-seventh of the diameter; in the writer's opinion the latter ratio leaves nothing to be desired. In the cases of the small diagonal mirror and of the small convex mirror, which cannot easily be supported at the back, the thickness should be not less than one-sixth of the diameter.

All mirrors should be polished (not figured) and silvered on the back as well as on the face, in order that both sides shall be similarly affected by temperature changes when the mirrors are in use in the telescope; for the same reason the method of supporting the large mirror at the back, in its cell, should be such that the back is as fully exposed to the air as possible.

The following is a brief description of the methods used by the writer in the optical laboratory of the Yerkes Observatory, in testing spherical, plane, paraboloidal, and hyperboloidal mirrors, while they are being figured. The methods of grinding, polishing, and figuring are not described here; these methods, and other matters relating to optical work, to the proper support of mirrors in their cells, and to the mountings of reflecting telescopes, will be described in a paper to be published in 1904 by the Smithsonian Institution.

In all cases the methods given enable the optician to test the mirror surfaces in a rigorous manner, as a whole, *i. e.*, without the use of zonal diaphragms or local tests of any kind. A great saving of time is thus effected; for testing should be done at frequent intervals during the work of figuring; frequently a mirror is tested a hundred times or more, as its figure is gradually improved. The tests are all conducted in the optical laboratory, which must be so arranged that temperature and atmospheric conditions are under perfect control. It is impossible to overestimate the importance of being able to test quickly, as often as is desired, and under conditions of constant temperature and quiet air — conditions which are seldom realized in a dome or out of doors. All mirrors when being tested are placed on edge, so that the axis of figure is nearly horizontal, large mirrors being suspended in a wide, flexible steel band lined with soft paper or Brussels carpet.

I. CONCAVE SPHERICAL MIRRORS.

The method of testing concave spherical mirrors is well known; it has been admirably described by Foucault, Draper, Common, and others. It is described briefly here, as it forms a necessary introduction to the tests of other forms of surfaces. A small, brilliant source of light, or "artificial star," may be produced by placing in front of the flame of an oil lamp a thin metal plate in which a very small pinhole has been bored. If the illuminated pinhole be placed about an inch to one side of the principal axis of the mirror, and at a distance from the mirror equal to its radius of curvature, a reflected image of the pinhole will be formed on the other side of the axis and at the same distance from it and from the mirror as the corresponding distances of the pinhole itself. If the surface of the mirror is perfectly spherical and there be no atmospheric disturbances in the course of the rays, the reflected image, when examined with an eyepiece, will be found to be a perfect reproduction of the pinhole, with the addition of one or more diffraction rings around it, minute details of the edges of the pinhole appearing as exquisitely sharp and distinct as when the pinhole is itself examined with the eyepiece. If the eyepiece be moved outside and inside the focus, the expanded disk in both cases appears perfectly round. Nothing can be more impressive than to see such a reflected image produced by a fine spherical mirror having a radius of curvature of one hundred feet or more. Several such mirrors of two feet aperture have recently been finished here.

The use of an eyepiece is interesting for such experiments as that just described, and is important as a check upon the test with the opaque screen. The latter test, however, which I shall call the knife-edge test, is used almost exclusively with mirrors of all forms; it is far more serviceable than the eyepiece test in determining the nature and position of zonal irregularities, and is far more accurate in determining the radius of curvature either of a mirror as a whole or of any zones of its surface.

If the eye be placed just behind the reflected image of the illuminated pinhole, so that the entire reflected cone of light enters the pupil, the polished, unsilvered mirror surface is seen as a brilliant disk of light. Let an opaque screen or knife-edge be placed in the same plane through the axis as the pinhole, and be moved across the reflected cone *from the left* and just in front of the eye; if a dark shadow is seen to advance across the mirror from the left, the pinhole and knife-edge are inside of the best focus and must be moved together away from the mirror; if, however, with the screen still moved across from the left, the shadow advances across the mirror from the right, pinhole and screen are outside of the focus and must be moved toward the mirror. By repeated trials a position is found in which the shadow does not appear to advance from either side, but the surface of the mirror darkens more or less uniformly all over; this is the position or plane of the best focus, and it is with this position of the knife-edge that irregularities of the surface, if any exist, are seen in most highly exaggerated relief; with this position of the knife-edge, the mirror, if perfectly spherical, is seen to darken with absolute uniformity all over, as the screen is moved across the focus, and the impression is given to the eye of a perfectly plane surface.

If, however, the mirror surface is not perfectly spherical, but contains several zones of slightly different radii of curvature—a very common case—the zones will appear as protuberant or depressed rings on an otherwise plane surface. The reason for this is evident; the light from some parts of such zones is cut off by the knife-edge before, from other parts after, the illumination from the general surface is cut off. The surface is therefore seen in light and shade, *i. e.*, in enormously exaggerated relief. The mirror must be regarded as being illuminated by light shining very obliquely along the surface from the side opposite that from which the knife-edge advances across the focus. The interpretation of the lights and shades becomes easy after a little experience; not only is the character of a zone—whether it be an elevation or depression—readily seen, but its diameter and its width are readily determined.

If the disk of glass is of sufficient thickness and of proper quality, and if attention has been given to the uniform rotation of the turntable on which the mirror is polished, and to the protection of the glass from abnormal conditions of temperature during grinding and polishing, all irregularities of figure which occur are perfect zones or rings concentric with the edge of the glass; that is, the surface is always a perfect surface of revolution. If, however, the disk is too thin, or has been improperly supported during grinding and polishing, or if it has been cut out of thick rolled plate glass so that it is weak in the direction of one diameter, an astigmatic mirror may be produced, in which the radius of curvature is slightly different along two diameters at right angles to each other.

Astigmatism is easily recognized with either the knife-edge or the eyepiece test. Let the plane of the apparent focus be determined with the knife-edge advancing from the left, then from above, then from the right, then from a number of directions between these three; if astigmatism exists, the planes of the various foci thus found will not coincide; and the directions of greatest and least curvature of the surface are readily determined. When the eyepiece test is used, an astigmatic mirror does not give a sharp image even at the best focus; if the eyepiece be moved outside or inside of this focus, the expanded disk becomes elongated and is not uniformly illuminated; the direction of elongation outside is at right angles to that inside, and the distribution of light in the expanded disk is entirely different outside and inside of the focus.

The general character of the tests having been described, let us consider some important matters of detail which are necessary for the greatest refinement in testing all forms of mirrors.

By the use of a small lens and a diagonal prism, in the manner shown in Fig. 1, the lamp may be kept well out of the way, and the illuminated pinhole and its reflected image brought very close to the axis of figure of the mirror. This is of much importance in testing mirrors of short focus or of great angular aperture, as the danger of errors in testing due to working considerably out of the axis of figure is avoided. As may be seen in the figure, the pinhole is now placed at the surface of the diagonal prism nearest to the mirror being tested. The arrangement should be such that the angle of the cone of rays proceeding from the lens is considerably larger than is needed to fill the concave mirror.

During the work of figuring, mirrors are usually tested while unsilvered, since very frequent tests are desirable. While the amount of light reflected from the polished unsilvered surface is surprisingly great, a much more brilliant artificial star than that given by the oil lamp is required for the greatest refinement and accuracy with the knife-edge test, especially in the cases of plane, paraboloidal and hyperboloidal mirrors, in which there are two reflections from the unsilvered surface. It might be supposed that a larger pinhole could be used, and thus a more brilliant illumination of the mirror surface secured; but a large pinhole allows an apparent diffusion of light over the mirror surface, which obliterates all of the more delicate contrasts of illumination, due to minute irregularities of surface. With feeble illumination of the mirror surface, the eye is entirely unable to detect slight contrasts which with brilliant illumination become strong and unmistakable. When the knife-edge test is used with an extremely small pinhole, of between 0.05 mm and 0.1 mm diameter, illuminated by acetylene, or (what is much better) oxyhydrogen or electric arc light, minute zonal irregularities are strongly and brilliantly shown, which are entirely invisible with a larger pinhole or insufficient illumination. With the arrangement of lens and diagonal prism (Fig. 1), either of the sources of light named can be used without difficulty; disturbances of the air from their heat should be prevented by placing the light behind a partition with a window of thin plate glass.

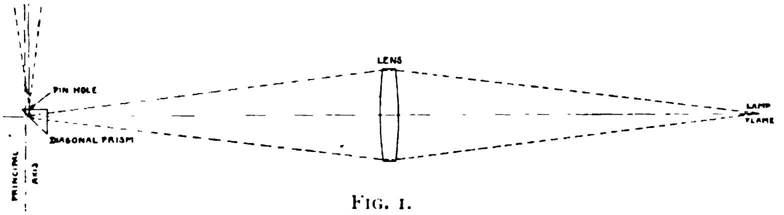


FIG. 1.

With the best conditions of apparatus just described the degree of accuracy to be attained with the knife-edge test is surprising. With a spherical mirror of two feet aperture and fifty feet radius of curvature, the plane of the center of curvature can be easily located to within 0.01 inch (0.25 mm), and, with care, to within half of that amount. With the dimensions given, a change of 0.01 inch in the radius of curvature corresponds to a change of $\frac{1}{5000000}$ inch (0.00005 mm) in the depth of the curve of the mirror surface. There can be no doubt that zonal irregularities of surface of half this amount are readily recognized.

A large and perfect spherical mirror is an indispensable part of the equipment of an optical laboratory, as it affords what is, in my opinion, the most satisfactory means of testing large plane mirrors. In making a paraboloidal mirror, also, it is best first to produce a spherical surface of the proper radius of curvature and then to change gradually to the paraboloid.

II. PLANE MIRRORS.

The making of large plane mirrors of fine figure is usually regarded as much more difficult than the making of large concave mirrors. The difficulty has been, in the past, largely one of testing. With a satisfactory method of testing a large plane surface *as a whole*, in a rigorous and direct manner, the problem is greatly simplified. So far as the writer is aware, no such test has hitherto been fully developed. In *Monthly Notices*, 48, 3, 1887, Mr. Common suggests, very briefly, the testing of plane mirrors in combination with a finished spherical one, and uses a diagram in illustration; but no details in regard to the method are given. This method has been developed and used for many years by the writer, in testing plane mirrors up to thirty inches in diameter. When this test is used, the difficulty of making a twenty-four-inch plane mirror which shall not deviate from perfect flatness by an amount greater than $\frac{1}{5000000}$ inch (to use an example similar to that given in the preceding paragraph) is neither greater nor less than that of making a good spherical mirror of two feet aperture and fifty feet radius of curvature, when it is required that the radius of curvature shall not differ from fifty feet by a quantity greater than $\frac{1}{100}$ inch.

A spherical mirror *A* (Fig. 2) which should not be smaller in diameter than the plane mirror *B*, to be tested, is figured with the utmost accuracy, special care being taken that no astigmatism, however slight, exists in it. The mirror *A* is silvered; *B* is polished and unsilvered. The mirrors may be set up as shown *in plan* in Fig. 2, the distance $cm + mf$ being equal to the radius of curvature of *A*; both mirrors hang on edge in steel bands, as already described. The light from the illuminated pinhole strikes *B*, is reflected to *A*, thence back to *B*, thence to a focus close beside the illuminated pinhole.

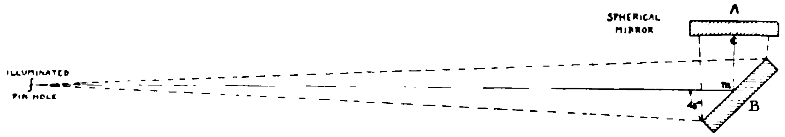


FIG. 2.

When using the knife-edge test the optician sees the mirror *B* brilliantly illuminated and in elliptical outline, the horizontal diameter appearing foreshortened by an amount depending upon the angle at which the mirror is viewed. With the knife-edge test the surface of *B* is seen in relief, as a whole; any zonal errors appear enormously exaggerated, and their character and position are readily determined, just as when a spherical mirror is tested at its center of curvature; these zonal errors of course appear elliptical on account of their foreshortening; their effect is doubled in intensity on account of the two reflections from *B* (assuming that the illumination is as brilliant as the eye requires).

The test as already described is all that is necessary for the detection and location of zonal errors. But something more is needed in order to detect general curvature, *i. e.*, general convexity or concavity in *B*. It is assumed that the mirror, when fine-ground and polished, is so nearly flat that no curvature can be detected with a Brown & Sharpe steel straight-edge of the finest quality. For convenience in description let us also assume that the surface is free from zonal errors. Let the knife-edge be moved across the reflected cone from the left; a focal point will be found at which the right and left sides of the mirror darken simultaneously; this focal point we will call f_1. Now let the knife-edge be moved across the cone from above, instead of from the left; a focal point will be found at which the upper and lower parts of the mirror darken simultaneously; this focal point we will call f_2. It is only when the mirror *B* is a perfect plane that f_1 and f_2 coincide with each other and with the point f (see figure). If *B* is slightly convex, both f_1 and f_2 are outside of f (*i. e.*, farther from the mirror than f), and f_1 is outside of f_2; if *B* is slightly concave, both f_1 and f_2 are inside of f, and f_1 is inside of f_2. In practice the exact position of f is not found, except incidentally when the plane mirror is finished, for this would involve the very accurate measurement of the large distance $cm+mf$. The determination of the positions of f_1 and f_2 with respect to each other is all that is needed.

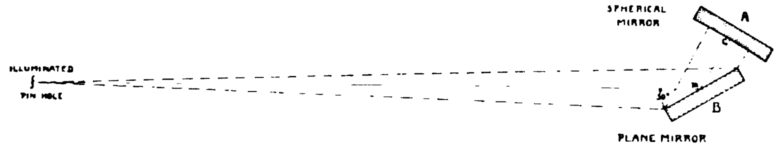


FIG. 3.

That f_1 and f_2 do not coincide when *B* is convex or concave is due to the fact that the curvature of *B* is apparently increased or exaggerated in the direction of the horizontal diameter of the mirror, on account of its foreshortening in this direction as seen from f; while the curvature in the direction of its vertical diameter is not thus exaggerated. The effect is precisely as if the spherical mirror *A* were astigmatic, the parts of the surface adjacent to the horizontal diameter having a different radius of curvature from those adjacent to the vertical diameter. This effect is so marked that an extremely small deviation of *B* from a true plane can be detected. For example, if *A* and *B* are each two feet in diameter, the radius of curvature of *A* being fifty feet as before, and if the angle which the line fm subtends with the surface of *B* is 45°, a departure from a true plane of $\frac{1}{350000}$ inch (0.00007mm) in the surface of *B* is readily detected. If the angle of the mirror *B* be changed to 30°, as shown in Fig. 3, the accuracy of the test for general curvature is about doubled; the latter position, however, is not usually so convenient for determining the positions of zonal irregularities; for the greatest refinement, therefore, the stand on which *A* and *B* are supported is so designed that the positions of the mirrors can be quickly changed so as to give the greatest accuracy in each part of the test.

The use of an eyepiece in this test is important because it shows how fatal to good definition is even a very slight convexity or concavity of a plane mirror when used in an oblique position. If f_1 and f_2 are made to coincide as closely as can be detected with the knife-edge test (*B* being free from zonal errors also) the reflected image of the pinhole, as seen with an eyepiece at f, is as exquisitely sharp and perfect as if it were formed by the spherical mirror *A* alone. But if *B* is very slightly convex or concave, the appearance of the eyepiece image is similar to that which has already been described in connection with astigmatic concave mirrors.

III. PARABOLOIDAL MIRRORS.

The methods of testing paraboloidal mirrors at their center of curvature, by determining the radius of curvature of successive zones, was brought to a state of great refinement by Draper, Common, and others. These workers used an eyepiece in determining the foci of the various zones. In the ASTROPHYSICAL JOURNAL for November 1901, **14**, 218, the writer described a modification of this test, in which the knife-edge instead of an eyepiece is used in determining the foci; with this modification very narrow zones or arcs can be used, and much greater accuracy attained in testing mirrors of large angular aperture, in which the curvature of the surface changes rapidly. In Fig. 4 is shown the diaphragm with which the successive zones were exposed in testing in this manner the large mirror of the two-foot reflector. The illuminated pinhole remains fixed in the plane of the center of curvature of the central parts of the paraboloid, *i.e.*, at a distance 2 *F* from the vertex, where *F* is the focal length; the plane in which the knife-edge must be placed to cause the right and left sides of a given zone to darken simultaneously is the plane in which the rays reflected from this zone are brought to a focus. When the paraboloidal figure is perfect, the rays reflected from any very narrow zone whose semi-diameter is R are brought to a focus at a distance $\frac{R^2}{2F}+\frac{R^4}{16F^3}$ back of the plane of the pinhole; *i. e.*, at a distance $2F+\frac{R^2}{2F}+\frac{R^4}{16F^3}$ from the vertex of the paraboloid.

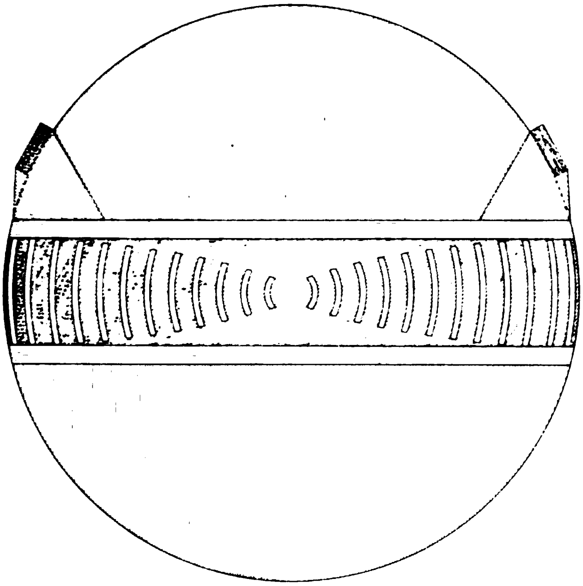


FIG. 4.

But when testing is done at the center of curvature, even with the extremely accurate method just described, the making of a large paraboloidal mirror of great angular aperture and really fine figure is an exceedingly difficult task. This is due in part to the necessity of very frequent tests, in each of which the foci of a large number of zones must be determined; it is due even more to the uncertainty in determining the exact nature of errors of surface (considering the surface as a whole), corresponding to focal readings which do not agree with the computed values. In the case of mirrors of small or moderate angular aperture much important information can be gained by viewing the surface as a whole from the (mean) center of curvature, by means of the knife-edge test; a finished paraboloid, when thus seen, appears to stand out in relief, in strong light and shade, as a surface of revolution whose section is that shown in Fig. 5. Knife-edge and pinhole are both in the plane of the center of curvature of the zone *a;* the apparent curve should be a perfectly smooth one. But in the case of a mirror of large angular aperture the change of curvature is so rapid that only a narrow zone can be well seen at one time, *i.e.*, with a given focal setting of the knife-edge.

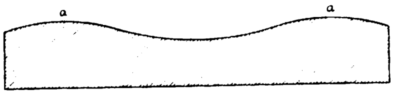


FIG. 5.

Attention has been called to the method of testing paraboloids at the center of curvature in order to contrast it with that next described, which is incomparably more simple, direct, and rigorous. The paraboloid is tested at its *focus* instead of its center of curvature. A brief note in regard to this method has already been published in this JOURNAL[1] by the writer. A well-figured plane mirror, which must not be smaller than the paraboloidal one, is necessary in order that the testing may be done in the optical laboratory. In practice a small diagonal plane is also used, to avoid the necessity of a hole through the center of the large plane. Both of the plane mirrors are silvered. The arrangement of mirrors is shown in Fig. 6. The diagonal prism is placed at *f*, with the illuminated pinhole very near to the axis; pinhole and knife-edge are in the same plane, at a distance from

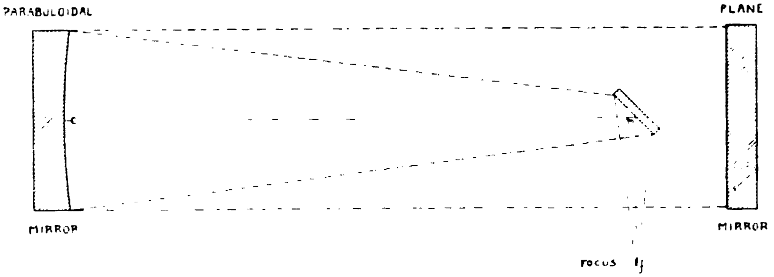


FIG. 6.

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[1] 14, 218, 1901.

the vertex equal to $cm + mf$, which is equal to the focal length of the mirror. The paraboloid is now tested as a whole, without the use of zones, precisely as a spherical mirror is tested at its center of curvature.

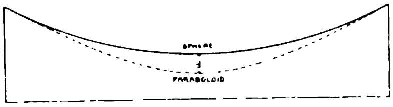

FIG. 7.

If F be the desired focal length of the paraboloidal mirror whose semi-diameter is R, then the spherical surface, which is fine-ground and fully polished preparatory to parabolizing, should have a radius of curvature of $2F + \frac{R^2}{4F}$. This is because parabolizing is done by shortening the radii of curvature of all the inner zones of the mirror, leaving the outermost zone unchanged, as shown in Fig. 7; this is a far easier and better method in practice than to leave the central parts of the mirror unchanged and to lengthen the radii of curvature of all the other zones, as shown in Fig. 8.

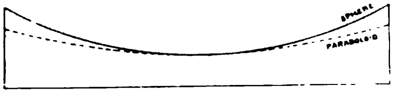

FIG. 8.

Let us now suppose that the concave mirror shown in Fig. 6 is spherical with radius of curvature $2F + \frac{R^2}{4F}$, where R is the semi-diameter and F is the distance $cm + mf$ from the center of the mirror surface to the plane of the pinhole and knife-edge. If the spherical surface be now viewed from the point f with the knife-edge test, it will appear to stand out in relief, in strong light and shade, as a surface of revolution whose section is shown in Fig. 9, the height of the protuberant center depending upon the angular aperture of the mirror.

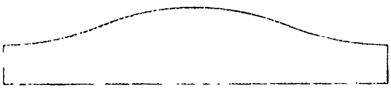

FIG. 9.

The reason for this appearance is readily seen by reference to Fig. 7. To change the spherical surface to a paraboloidal one, the protuberant center must be removed by the use of suitable polishing tools, until the surface, as seen with the knife-edge test from the point f, appears perfectly flat, *i. e.*, the illuminated surface darkens with perfect uniformity all over. As the paraboloidal surface nears completion, an elevated or depressed center, a "turned-up" or "turned-down" edge, or protuberant or depressed zones, can be seen, and their character and exact position be determined, with precisely the same ease and certainty with which similar irregularities are seen when a spherical mirror is examined at its center of curvature with the knife-edge test.

The actual difference of depth at the center or vertex, corresponding to *d*, Fig. 7, between a paraboloid and the nearest spherical surface, is small for such angular apertures as are used in practice. In the case of the mirror of the two-foot reflector, the focal length of which is only 236 cm (93 inches), the difference *d* is almost exactly 0.01 mm or 0.0004 inch; it is unusually large in this case on account of the exceptionally great ratio of aperture to focal length. The quantity *d* varies as the fourth power of the diameter of the mirror and inversely as the cube of the focal length. In the case of Lord Rosse's mirror of six feet aperture and 54 feet focus (ratio 1 to 9) the corresponding difference is only 0.0001 inch, very nearly; while in the case of the five-foot mirror of the Yerkes Observatory of twenty-five feet (762 cm) focus this difference is about 0.0006 inch (0.015 mm).

It should be noticed that even when the pinhole and reflected image are very near each other, as they should be, both may be far out of the axis of the paraboloid, if the mirrors are not perfectly adjusted or collimated; when this is the case, the mirror surface, when seen with the knife-edge test, does not appear as a surface of revolution, and cannot be properly tested. There are several simple methods of collimating the mirrors, thus insuring that the pinhole and the reflected image are both extremely near the optical axis; these methods need not be described here. The frame which supports the concave mirror can readily be so designed that this mirror can be removed and replaced repeatedly, while figuring it, without sensibly disturbing the adjustments.

The difficulties of making short-focus paraboloidal mirrors of fine figure are so greatly reduced when this method of testing is used that I believe that the general adoption of this method by opticians would lead to such an improvement in results as to bring about a marked advance in the usefulness of reflecting telescopes. The making of the large plane mirror which is necessary in this test becomes so simple and certain when the method of testing described earlier in this article is used that I have no hesitation in saying that when a large paraboloidal mirror of short focus and of the finest attainable figure is to be made, it is economical to make a plane mirror of the same size with which to test it, if one is not already available. The concave mirror is first figured spherical, and is used thus in testing the plane mirror while the latter is being figured; the plane mirror is then used in testing the concave one during the parabolizing of the latter. Both the plane and paraboloidal mirrors are then used in testing the (convex) hyperboloidal mirror while the latter is being figured.

IV. HYPERBOLOIDAL MIRRORS.

The methods of figuring and rigorously testing convex hyperboloidal mirrors are now so thoroughly developed that the reflecting telescope can be regarded as a universal photographic telescope of the highest class, capable of giving, at the focus of the paraboloidal mirror of large angular aperture, the finest photographs now attainable of large and excessively faint objects such as the nebulæ in general; while by the addition of the small convex mirror a great equivalent focal length is obtained for the photography of bright celestial objects requiring large scale, such as the Moon, the planets, the dense globular star-clusters, and the annular and planetary nebulæ. The convex mirror of course serves as an amplifier, and possesses the great advantages over a lens used for this purpose that the perfect achromatism and the high photographic efficiency of the reflector are retained, and that the mechanical arrangements are very compact and economical. In order to give perfect definition the convex mirror must be an hyperboloidal one.

Fig. 10 shows the arrangement of mirrors employed in the two-foot reflector when used as a Cassegrain, a small diagonal plane mirror being used at *m*. *P* is the paraboloidal mirror with its focus at f; H is the hyperboloidal mirror; the secondary focus or magnified image produced by the combination being at F; the point c is the center of the hyperboloidal surface. Calling the distance $fc = p$, and the distance $cm + mF = p'$, then $\frac{p'}{p}$ represents the amount of amplification introduced by the convex mirror. The radius of curvature R of the spherical surface, to which the convex mirror is ground and polished preparatory to hyperbolizing, is found with sufficient accuracy for all practical purposes by the formula $\frac{1}{p} - \frac{1}{p'} = \frac{2}{R}$, whence $R = \frac{2pp'}{p' - p}$.

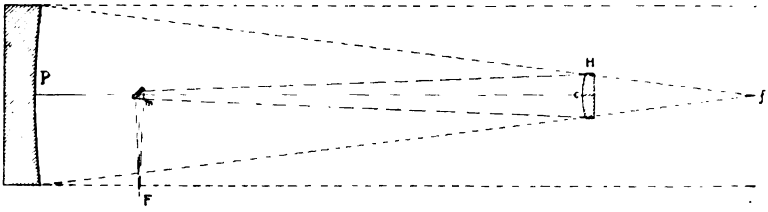

FIG. 10.

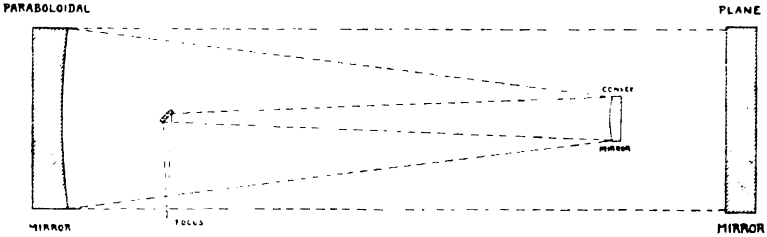

FIG. 11.

The method of testing the convex mirror while hyperbolizing it is shown in Fig. 11. The illuminated pinhole is placed very near the axis at F. The diverging cone of light strikes the small plane mirror, then the convex, then the large paraboloid, whence, if all the mirrors are finished and are well adjusted or collimated, the light is reflected in a parallel beam to the large plane; returning, the rays are brought to a focus very near the axis of figure and in the plane of the illuminated pinhole. All of the mirrors except the convex one are silvered. The convex spherical surface with radius of curvature R, as above described, when viewed with the knife-edge test from the point *F*, presents the same general appearance of a smoothly curved surface of revolution, in strong light and shade, which a paraboloidal surface presents when similarly viewed from its center of curvature (see Fig. 5). All that is necessary to produce the hyperboloidal surface is to soften down, with suitable polishing tools, the apparent broad protuberant zone between the center and edge, until the mirror, as seen from *F*, appears perfectly flat; *i. e.*, until the illuminated surface is seen to darken with absolute uniformity all over when the knife-edge is moved across the focus.

As in the case of the paraboloid, it is necessary in this test that all of the mirrors be lined up or collimated with care; otherwise the surface of the convex mirror will not appear as a surface of revolution, and cannot be properly tested. The axes of the paraboloid and hyperboloid must coincide, and the face of the large plane mirror must be at right angles to these axes. In practice these adjustments are not difficult, and when they are once effected the convex mirror can be removed from its cell and replaced, while being figured, without sensibly disturbing them.

YERKES OBSERVATORY,
December 10, 1903.

MICHELSON'S THEORY OF THE DISPLACEMENT OF SPECTRAL LINES.[1]

By J. Fényi.

Professor Wladimir Michelson has very recently given an entirely new and trustworthy explanation of the displacement of spectral lines on the Sun, which is distinguished from the bold hypotheses advanced in recent years by the facts that it is not only based upon an unassailable scientific foundation, but also that it finds an astonishing confirmation in the observations of these remarkable phenomena. Michelson shows that a displacement of lines must occur when a denser mass is introduced in the path of a ray of light. I will first give here another derivation of the appropriate formulæ, in order to make possible a test of the applicability of this theory, which is of such importance for the correct interpretation of solar phenomena. In the above figure the line $E\,F$ denotes the surface of separation of the mass M, at the right, from the ether A, at the left; a and b represent the length of a light-wave emerging into the ether from the mass, supposed at rest. As the end of the wave emerges at the point a, its front will have advanced in the ether to a'; the wavelength in ether, which we will designate by λ_e, is

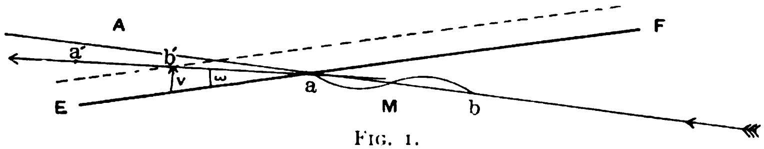

Fig. 1.

$$\lambda_e = aa' = abn ,$$

where n is the index of refraction. The color of the light then remains unchanged, and the spectral lines are not displaced.

But if the mass is in motion at right angles to the wave of light, as indicated by the arrow, the front of the wave will similarly emerge into the ether at a, and will also similarly have reached a' when its rear arrives at a; but the rear will not yet have emerged at a into the ether, since it must travel farther, to b', in order there to overtake the boundary of the mass which is in the meantime intervening. While this distance is traversed in the mass the front of the wave must pass beyond a' over the distance $ab'n$ in ether. We therefore have for the wave-length in ether:

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[1] A similar paper, in Latin, is published in the *Memorie della Pontifica Accademia dei Nuovi Lincei*. **21**, 1903.

for mass at rest,

$$a'b' + b'a = \lambda_0 ,$$

for mass in motion,

$$a'b' + b'an = \lambda_1 ,$$

whence

$$\lambda_1 - \lambda_0 = b'a(n-1) . \qquad (1)$$

The distance $b'a$ will be traversed by the intruding mass in the same (apparent) time in which the light passes in ether over the distance $aa' + ab'n$. Therefore if we designate this apparent velocity of the mass by c, that of light in ether by V, we get

$$\frac{ab'}{aa' + ab'n} = \frac{c}{V} , \text{ or } \frac{ab'}{\lambda_1 + ab'} = \frac{c}{V} ,$$

whence we obtain

$$ab' = \frac{c}{V - c} \lambda_1 .$$

Substitution of this value in equation (1) gives the precise formula

$$\lambda_1 - \lambda_0 = \frac{c}{V - c} (n-1) \lambda_1 . \qquad (2)$$

If the mass, acting as a source of light, were to move in the line of sight with a velocity v, the change in the wave-length would be calculated on Doppler's principle with the same precision by the formula

$$\lambda_1 - \lambda_0 = \frac{v}{V - v} \lambda_1 . \qquad (3)$$

For practical computation we may place

$$\lambda_1 - \lambda_0 = \frac{v}{V} . \lambda_1 ,$$

where we neglect the velocity of the source as very small compared with that of light. In the case before us we cannot similarly neglect c as compared with V, as the calculation of c leads to enormous values.

We therefore obtain a different alteration of wave-length when the ray passes from the ether into the mass, and not from the mass into the ether as above assumed. In this case the alteration of the wave-length, under otherwise equal conditions, is determined by the formula

$$\lambda_1 - \lambda_0 = \frac{c(n-1)}{V+c}\lambda_0 \, , \tag{4}$$

while in the first case we had, instead of equation (2),

$$\lambda_1 - \lambda_0 = \frac{nc(n-1)}{V-nc}\lambda_0 \, , \tag{5}$$

where the alteration of the wave-length is similarly represented by λ_0.

If the mass intrudes into the path of the ray in the opposite direction, we have only to give the opposite sign to c in the above formulæ.

In order to judge of the applicability of Michelson's explanation to solar phenomena, let us first consider the case represented in Fig. 1 of the emergence of the ray into the ether, which causes the greater displacement of the line.

A comparison of equations (3) and (2) indicates that if the alteration of the wave-length is to be the same according to Doppler as according to Michelson, then we must have

$$\frac{v}{V-v} = \frac{c}{V-c}(n-1) \, . \tag{6}$$

It may be seen from Fig. 1 that

$$c = v \cot \omega \, . \tag{7}$$

On eliminating c from (6) by this equation, we get the equation of condition

$$\tan \omega = \left(1 - \frac{v}{V}\right)\left(n - 1\right) + \frac{v}{V} \, .$$

In order to test the validity of Michelson's explanation we must now introduce assumed numerical values into the formula. We will assume at the start that the velocity of the mass, which is to be taken as equal in the two cases, is 300 km per second. This is about the largest velocity that is observed at the time of the maximum solar activity, perhaps once or twice in a year, both in direct ascent and by the displacement of the line according to Doppler's principle. Therefore the intruding mass, according to Michelson's view, is rising with the similar velocity of 300 km at right angles to the emerging ray of light. With this value

$$\tan \omega = 0.999\,(n - 1) + 0.001 \ ,$$

and with the omission of the factor 0.999, as it only affects the sixth decimal, which will not be included in our discussion,

$$\tan \omega = (n - 1) + 0.001 \ . \tag{8}$$

The direction of the motion has been wholly left out of consideration above, as it is of no consequence for the purposes of comparison. We will therefore assume that a mass of hydrogen is rising from the Sun into empty space, and that the light emerging from the interior of the mass at the bounding surface inclined to the ray suffers the same change of wave-length as if the mass should move in the line of sight. The following table contains the numerical values for the different quantities computed according to our equation of condition. D denotes the density of the hydrogen, n its index of refraction referred to a vacuum, and c and ω are as above:

D ($H=1$)	n	c	ω	Maximum Refraction	Altitude	Duration
		km				secs.
1.5	1.0002	248,000	4° 8′	0 48	..	1
15	1.00208	97,000	10 36	3 42	2	2
50	1.00695	37,700	27 20	6 44	8	5
100	1.0139	20,000	51 20	9 34	12	10

The fifth column contains the greatest deviation possible for a ray entering into the mass of the given density from the ether at an angle of incidence of 90°. The values permit us to judge whether the photospheric light could be refracted to the observer by the assumed mass. The sixth column gives the altitude in geocentric seconds (″) at which such a refraction could take place. In column 7 is stated the duration of the displacement at that place if the intruding mass shall not occupy a space of over 200,000 km. We notice that even on the assumption of a density of 100 (that of hydrogen being unity) no explanation is possible in this simple manner. The value of c comes out so large that in thirty seconds the mass would have to intrude to an enormous expanse, almost equaling the solar radius. It is not permissible to assume a greater density, for even at 100 a hydrogen mass in empty space exhibits a maximum refraction of $9° 34'$. It would therefore necessarily happen occasionally that such a mass would refract the light of the photosphere toward the observer, who would then see a portion of the photosphere at an approximate altitude of 12″ above the solar limb. Anything of that sort would be easy to see, but has never been observed. This difficulty does not arise at a slighter density, because the altitude resulting would be included within the chromosphere, where the mass would not yet have reached empty space. Hence a displacement lasting for from three to five minutes at the same place, such as is commonly observed, cannot be explained as the result of the elevation of the mass.

The difficulty cited does not occur, however, if we assume that a streamer slightly inclined to the direction of the ray rises with the assumed velocity. The quantity c then has no significance. The wave-length of the ray emerging from the interior will be continuously altered by the intrusion of the mass itself; and, as is specially noteworthy, the wave-length will be increased if the streamer is inclined downward with respect to the observer and decreased if it is inclined upward. This explains a displacement of the line toward the red as well as toward the blue, while according to the former assumption the elevation of a compact mass can only have the effect of lengthening the wave. The change of the displacement is also explained without any difficulty, although this offered the greatest obstacles to an explanation on Doppler's principle, for that assumed alterations of the velocity of from 200 to 300 km during a few minutes, which would predicate quite incredible accelerating or retarding forces. This change of the velocity is explained in an entirely simple manner by the assumption that the streamer does not rise up with precisely the same velocity throughout its whole length —indeed, it would be most remarkable if it should.

An excellent confirmation of Michelson's explanation is also found in the details of observation, since a continuous and considerable variation of the displacements which occur in prominences high above the solar limb is almost always observed, and hardly ever does the displacement remain unchanged for more than a few minutes; while on the explanation by Doppler's principle a uniform displacement evidently ought to be observed, because every motion remains the same unless disturbed by the development of other forces.

A similarly easy and natural explanation is also found for the striking occurrence of opposite displacements in quick succession, particularly in prominences; it is only necessary to assume that the mass is wedge-shaped, with its upper surface inclined backward with respect to the observer, and its lower surface forward.

Another fact, in the best of agreement with this explanation, is that displacements of the spectral lines, particularly at high elevations, as a rule accompany the uprisings of prominences which of themselves are seldom powerful. This fact, however, offers no special difficulty to the explanation on Doppler's principle.

It is, indeed, the fact that I have myself given an entirely different explanation of all these remarkable phenomena, but it is none the less necessary, even if my explanation does correspond with the facts, to yield a place to that of Michelson, according to which the displacements of lines on the Sun, although they cannot all be explained, are nevertheless considerably modified as to their magnitude and significance. The only thing which can be raised against the above explanation according to Michelson would be the smallness of the angle, which can hardly exceed 30′. The bounding surface, therefore, cannot be exactly plane, but irregularities will only cause the displaced spectral lines to appear diffuse, which is not in contradiction to the observations, as a diffuse character is the more common, particularly where the displaced line seems blurred in the direction of the normal position.

The smallness of the angle offers a more serious difficulty by too greatly limiting the elevation at which the stream appears to the observer. If we assume the density of the ascending stream to be 50, the inclination of the corresponding surface would be 27′20″. Therefore, if the place at which the displacement occurs should subtend an angle of 1″ in elevation for the observer, the streamer would have to be 78,500 km long, that is, about 126″ geocentric, or 8° on the Sun's limb. This is a very considerable extent, but nevertheless not too great to be assumable, according to observations made elsewhere. One second of elevation is very little, however, and hence the displacements of much greater extent, which are often seen, cannot be explained in this simple manner.

Michelson, however, seems to lay the principal stress on the effect of a prism-shaped mass of high refractory power, which rapidly intrudes into the path of the rays and thus causes a very decided change of the wave-length. He developes a formula in a somewhat complicated manner, from which it follows that if the prism deviates the ray by 60°, the wave-length will be changed by the sudden intrusion as much as if the source of light were to move in the line of sight with the same velocity. From what has been said above we can solve this problem very simply. If a ray of light enters a prism, which is elevated with its edge upward, on one face from the ether into the mass, and on the other face from the mass into the ether, formulæ (5) and (4) will be applicable. It follows from these that the change of the wave-length, though not the same at the two surfaces, is in the same direction, that of increasing the wave-lengths at both contacts. If the edge was downward, the wave-lengths would be diminished in the same degree. Michelson's assumed case with a deviation of 60° is not, however, applicable to the explanation of displacements of lines above the photosphere, in the prominences. We cannot admit that masses of such density rise above the photosphere, because the maximum refraction of 30° due to such masses would necessarily, with corresponding form and position, refract the light of the photosphere toward the observer: a portion of the photosphere would necessarily be seen above the limb, which never has been observed. It is not here disputed that such a refraction can be assumed to occur below the surface of the Sun when vapors of greater refractive power than hydrogen are presumed to be effective.

We can use the above-mentioned action of prismatic masses, however, with great advantage in explaining large local displacements of lines without making abnormal assumptions. Let us regard the above-considered surface of a rising streamer to be, not plane, but covered lengthwise with wave-like structures, which might be roughly treated as prisms with their edges upward. The ray emerging from the interior may then pass through two prisms in order to reach the observer. Equal inclination being assumed, the change of the wave-length would be about five-fold; hence we should get the same displacement as at a simple emergence except with five-fold greater inclination (ω) of the surfaces, or with five times smaller velocity (v) of the mass. It is further known from observations that the large prominences which rise rapidly commonly consist of several parts. Each of these can be regarded as composed of two prismatic portions, one with the edge upward, the other downward. If several portions should happen to lie behind each other for the observer, the light coming from the outside one would have to traverse the intervening rising prismatic masses; the effect of all will be summed up and the same large displacement will be produced without the necessity that the refracting surfaces should have such exceedingly small inclinations. It should, indeed, be remarked that in this case light which has been altered in different degrees is integrated to the observer, so that the displaced light cannot appear separated from the normal line by a clear space. Here the observations also are in good agreement.

We may find an interesting confirmation of this theory in the peculiar appearance of rapidly rising prominences, for they show, in spite of their extraordinary brilliance, such peculiarly diffuse edges that the observer is prepared by their appearance for the phenomenon of an eruption. This peculiarity is a necessary consequence of the fact that the rising portions must always have more or less strongly inclined lateral surfaces. The inclination must always be greatest at the edges. The displacements will, of course, ordinarily be too small and have too slight an extent to be recognized from the spectral lines. The displacement will, however, be recognized by a diffuse appearance for which the eye is very sensitive; but it is this which has already actually been noticed in observations made hitherto.

We can summarize the results of the above discussion as follows:

1. Michelson's explanation has a sound theoretical basis and is also confirmed by observation.

2. The theory permits a particularly easy explanation of the very peculiar displacements at high elevations of the prominences, but not in every case, so that, while more or less consideration must be given to Michelson's explanation, the hitherto accepted explanation on Doppler's principle cannot be regarded as supplanted.

3. On the assumption that both explanations are based upon the same absolute velocity of the mass, we cannot deny that Michelson's view has the advantage of assuming a vertical direction of motion, while the development of such enormous velocities in the line of sight on the Sun cannot in general be assumed without grave doubts.

In respect to the latter statements I would offer the following evidence: The explanation, on Doppler's principle, of line displacements on the Sun can never be done away with, because the observations prove that such phenomena must be noticed. For occasionally rapidly rising streamers from prominences are observed which are inclined only 30° to the Sun's horizon. If such a streamer is inclined toward the observer and rushes up with a velocity of 300 km, the component in the line of sight will cause a displacement corresponding to a velocity of 260 km. I would cite as an example of this sort the eruption of such a streamer which was observed by me on June 1, 1900, and incidentally mentioned in the description of the great prominence rising at that time. The streamer appeared in projection inclined 60° toward the horizon, and rose in vertical projection with a velocity of 70 to 80 km. Hence it follows that the horizontal component would be from 35 to 40 km, so that, if this rising streamer had been inclined toward the observer, the corresponding displacement would necessarily have been presented, in an upward direction.

KALOCSA, HUNGARY,
October 4, 1903.

MINOR CONTRIBUTIONS AND NOTES.

RECENT SPECTROGRAPHIC OBSERVATIONS OF *NOVAE* WITH THE CROSSLEY REFLECTOR.[1]

THE following observations were obtained with the slitless spectrograph attached to the Crossley reflector:

NOVA AURIGAE.

A negative was obtained on August 29 and 30, 1903, with a total exposure of five hours.

The spectrum shows some decided changes since the previous observations by Stebbins on September 13, 1901.[2]

In 1901 the nebular line at $\lambda 501$ and the lines $\lambda 462$, $\lambda 434$, and $H\delta$ were bright and of about the same intensity. There was also a trace of the band at $\lambda 374$ at that time. *The recent observations fail to disclose any trace of the nebular line at* $\lambda 501$.

Although the plates used in the two cases were of different emulsions, they were of the same make. Other spectrograms taken with these emulsions show them to be about equally sensitive in the region of the chief nebular line.

The lines at $\lambda 462$, $\lambda 434$, and $H\delta$ are about equal to each other in brightness on the recent spectrogram and appear to have decreased in intensity relatively to the continuous spectrum since 1901. There seems to be little change in the band at $\lambda 374$. The magnitude of the *Nova* is now about 14. The 13½ magnitude star at a distance of $2'$ from the *Nova*, in position-angle 40°, gives a spectrum closely resembling that of *R Leonis* and similar variables when near maximum. No variations of brightness are shown, however, on the few plates of this region, which have been secured.

NOVA PERSEI.

A spectrogram was secured on July 30, 1903, with an exposure of 2 hours 3 minutes. Striking changes have taken place since the previous observations of October 1901, by Mr. Stebbins, and of January and March 1902 by Mr. Palmer.

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[1] *Lick Observatory Bulletin* No. 48.

[2] *L. O. Bulletin* No. 35.

The intensities of the lines have decreased very much, relatively to the continuous spectrum, which is now quite strong. *Hβ* is barely distinguishable, having decreased in intensity materially in the interval. The radiations at λ434 appear to have become relatively fainter, while *Hδ* seems to have suffered only the general decrease in intensity. The greatest change is in the radiations at λλ339 and 346. In October 1901 the latter line was the second brightest line in the spectrum, and the former was very strong. The observations of January and March 1902 showed a slight relative weakening in these lines. In the recent observations the line at λ339 *has disappeared entirely* and that at λ346 is distinguishable only as a very slight brightening in the continuous spectrum, the latter extending to λ334. The nebular line at λ501 seems to be but little changed in brightness.

A spectrogram obtained with the small slit-spectrograph on February 17, 1903, under rather poor conditions, confirms the great loss of radiations at λλ339 and 346. No trace of either of these lines is to be found on that plate, but as the focus is poor in that region, the only conclusion which can be drawn is that these lines could not have been nearly so bright as in 1901 and 1902.

Nova Persei was estimated to be of 11½ or 12 magnitude on July 30.

NOVA GEMINORUM.

Spectrograms of *Nova Geminorum* were secured on August 28 and 31, and on September 2. The last, having an exposure of 1 hour 30 minutes, is the best, but, owing to the great amount of smoke in the air, it is not so dense as the others.

A number of changes in the interval of three and a half months since the observation on May 11 are noticeable. The entire spectrum has grown much fainter. The nebular line at λ501 has become relatively stronger, while *Hβ* has become exceedingly faint. *Hδ* has also become weak. The line at λ434 is now very much the strongest line in the spectrum. Its great strength may be due to the influence of the line at λ436, which cannot be separated with the dispersion used. The line at λ463 is very much broadened, and is probably composed of several lines, too close for separation with the instrument used. There are also very faint traces of the higher hydrogen lines on the background of continuous spectrum. Owing to the greater transparency of the atmosphere on August 28 and 31, the spectrograms obtained on those nights show a greater density in the ultra-violet, where a faint maximum can be seen in the region of the line at λ346.

A careful comparison of the entire series of spectrograms of *Nova Geminorum* obtained with the Crossley reflector discloses some facts in connection with the development of the extreme ultra-violet lines. A number of spectrograms were obtained between April 2 and 8, all of which show a bright maximum in the continuous spectrum, the position of the center of which was found to be at λ350 in two instances and at λ352 in another. The next observation was on April 18. It gives no indications whatever of any maxima in the well-marked continuous spectrum of this region. The next observations, secured on April 26, *show a maximum at λ346, but none in the region of λ350.* The observation of May 11 (the last before interference by the Sun) also shows the maximum at λ346 observed on April 26, but no stronger, and without any trace of the maximum at λ350. The observations of August 28 and 31 show a maximum of similar relative intensity at λ346.

These observations seem to prove conclusively that the line at λ346 made its appearance in the spectrum of *Nova Geminorum* between April 18 and 26, and that just previous to its appearance a brightening, slightly lower in the spectrum, disappeared. No certain indications are to be found of the line at λ339 which was strong in *Nova Persei.*

The apparent absence of the line at λ339 in *Nova Geminorum*, even were it known that there is any relation between it and λ346, would not be significant. In *Nova Persei* λ339 was not nearly as strong as λ346, and even the latter is weak in *Nova Geminorum.*

It would be of great interest to know the history of this ultraviolet region from May 11 to August 28, but unfortunately the Sun interfered and the limited zenith distances at which the Crossley reflector mounting could be used prolonged the interval. On September 2 the seeing was very steady, and the spectrum was examined visually. The nebular line at λ501 was very sharp and distinct, and contained nearly all of the light in the visual spectrum. A line was suspected in the yellow, but could not be confirmed.

The magnitude of *Nova Geminorum* was estimated to be 12 during the recent observations.

The foregoing observations suggest additional facts to be taken into account when considering the physical conditions of the *Novae.*

The line at λ346, which was discovered by Mr. Palmer to exist in some of the nebulæ, appeared in *Nova Geminorum* at about the same as, or a little later than the nebular line at λ501.

The line at λ346 and its companion at λ339, although among the strongest in the spectrum of *Nova Persei*, were the first to disappear.

In *Nova Aurigae*, which has reached a later stage than either *Nova Geminorum* or *Nova Persei*[1] we have observed the extinction of the nebular line at λ 501, since 1901, and a closer approach to the ordinary type of stellar spectrum.

It can scarcely be doubted that the spectra of the three recent *Novae* are destined to attain the same character as those of the great majority of the stars, and as that which Palmer[1] has shown *Nova Cygni* to have reached—*i, e.*, a continuous spectrum without bright lines and that the whole cycle of changes will occupy but a few years, even in the case of so great an outburst as that of *Nova Persei.*

Mr. Sebastian Albrecht, Fellow in Astronomy in the Lick Observatory, has rendered efficient assistance in making all the recent observations with the Crossley reflector.

C. D. PERRINE.

SEPTEMBER 9, 1903.

VISUAL OBSERVATIONS OF THE SPECTRUM OF *NOVA GEMINORUM* MADE WITH THE THIRTY-SIX INCH REFRACTOR.[2]

THE spectrum of *Nova Geminorum* was observed visually on the mornings of August 17 and 18 with Spectrograph I attached to the thirty-six inch refractor. The three chief nebular lines were well developed, $H\beta$ being faint, λ 4959 somewhat stronger, and λ 5007 relatively very much more intense. There was also a very faint line near λ 4700, but too faint to identify with accuracy. Nothing could be made out either at D or H_α. As far as could be judged, considering the faintness of the object, there was very little continuous spectrum, and the lines were sharp and well defined.

A plate of this region taken on April 6, 1903 (*cf. L. O. Bulletin* No. 37), showed a faint trace of λ 5007, probably just beginning to appear. At present this line is the most conspicuous object in the visual spectrum, and in it is concentrated nearly all the light in this region. The change to the nebular type seems complete.

H. D. CURTIS.

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[1] *L. O. Bulletin* No. 35.

[2] From *Lick Observatory Bulletin* No. 48.

ERRATA.

Astrophysical Journal, Vol. **18**, October, 1903, in Professor Hartmann's article on "A Revision of Rowland's System of Wavelengths:"

Page 168, ninth line from foot, *for B*, *read A* and *B*.

Page 174, seventh line from top, *for* 5826.582, *read* 5862.582.

Page 182, at head of first column of Table VII, add λ.

Page 185, first line from top, *for* standard, *read* standards.

Page 185, thirteenth line from top, *for* -9, *read* -11.

Page 189, fifteenth line from top, *for* in order to refer them, etc., *read* and referred to the solar spectrum, we have.

Page 189, nineteenth line from top, *for* λ, *read* $\lambda_{\odot}$.

THE
ASTROPHYSICAL JOURNAL
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VOLUME XIX MARCH 1904 NUMBER 2

SPECTROGRAPHIC OBSERVATIONS OF STANDARD VELOCITY STARS AT PULKOWA.

By A. BÉLOPOLSKY.

THIS paper gives only the provisional results of the investigations of the velocities of the international fundamental stars. The new spectrograph of the Pulkowa Observatory was made by O. Töpfer, of Potsdam, according to his model III, and may be regarded as a duplicate of the Potsdam spectrograph III A. It has a collimator of 550 mm focal length, three simple flint prisms, and two cameras, designated as A and B, of respectively 610 and 415 mm focal length. The prisms are set at minimum deviation for $H\gamma$. The whole spectrograph is provided with Hartmann's automatic heating device.

The spectrum of iron has been for the most part used for comparison. Until October 9, 1902, a Ruhmkorff coil with four Leyden jars gave the spark spectrum. Since that date I have employed an arc lamp of 100 volts and 2-4 amperes. A ground-glass disk is placed between the arc and the slit when the comparison spectrum is being taken.

The uniformity of intensity of the beam of light emerging from the collimator lens was tested by introducing a photographic plate. It turns out that the lens is uniformly illuminated for the artificial source, but this is not the case for the stars (*α Lyrae* and *α Aurigae*). For western hour angles the upper half of the lens is more strongly illuminated, for eastern hour angles the lower. When the correcting lens was removed, there appeared to be a diametral zone, parallel to the slit, having but faint illumination. In this, perhaps, lies the reason why on our spectrograms the stellar lines always appear to be inclined with respect to the comparison lines, if the star's image has been rigorously kept at the same point on the slit. I will here pass over the other investigations of the spectrograph which I have made according to Hartmann's methods.

I must admit that I am not satisfied with any of our spectrograms, since, in spite of all my efforts, the lines never seem sharp enough. I cannot now decide whether the cause lies in the thirty-inch objective, which gives much diffuse light, or in the prisms.

Stars fainter than the third magnitude, situated near the equator, can be observed at Pulkowa only with difficulty, for the two reasons: (1) the strong absorption of the ultra-violet rays, and (2) the increase in size of the star's disk with decreasing altitude. The necessary exposure time is thus greatly increased for such stars, which explains why I have been unable to observe *γ Piscium*. I would remark in general that for fundamental velocity determinations only such stars should be selected as do not require too protracted an exposure.

The number of my observations is greater than according to the program, for the reason that the spectrograph was received only shortly before the work began, and the changes made during the investigation of the spectrograph rendered a repetition of the observations desirable. The weather hindered my securing the plates on the dates of the program.

The measurements were made with the old Töpfer microscope. The screw was investigated three times, each revolution being separately measured. I employed a magnifying power of one thousand in these investigations. The small corrections were applied to the readings for the settings on the stellar lines. The pitch of the screw is ¼ mm. In measuring the stellar spectra, I have usually employed a magnifying power of 20. The stellar spectrograms taken with camera A are measurable for an extent of 29 mm; with camera B, 25 mm. Each plate was twice measured; with the violet respectively toward the left and toward the right, and the mean was taken from the two measures. At the conclusion of a set of measures I convinced myself that the position of the plate had remained unchanged during the operation.

In the reductions I followed for the most part Hartmann's methods.[1] The constants of the formula I computed for the cameras for a temperature of 0° C. For this the measures of the iron comparison lines on each stellar plate were used after they have been reduced to 0° C. by a curve. The normal readings thus obtained for the iron comparison lines gave the reference points for each plate. I formed the differences, Normal—Plate, smoothed them out, and employed the adjusted differences for reducing the stellar lines to the normal scale. The wave-lengths could then be computed from the formula, and after comparison with Rowland's wave-lengths the displacement and finally the velocity in the line of sight were obtained. The reductions to the Sun were made with Schlesinger's tables, and are designated by V_a. V_d is the correction for the diurnal motion, and C that for the curvature of the lines computed for the mean wave-length. The corrections are as follows for the two cameras, for a mean wave-length of 432 $\mu\mu$, for three arguments:

CAMERA B		CAMERA A	
Argument	*C*	Argument	*C*
0.57 rev.	−0.28 km	0.78 rev.	—0.07 km
0.89	—0.55	1.00	0.14
1.92	−2.21	3.00	−0.41

In the selection of the wave-lengths from Rowland's table a certain arbitrary element has appeared, which may change the velocities obtained by 2 km. As illustrations of this I give below the velocities of *β Geminorum*, *α Boötis*, and *γ Cephei*.

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[1] *A. N.*, 155. 81–118, 1901.

The dispersion and scale for the two cameras are as follows:

Camera A			Camera B	
λ 4207	47′ per t.-m.	7.2 t.-m. per mm	λ 4205	10.5 t.-m. per mm
4297	41	8.4	4325	12.9
4427	33	10.2	4525	17.1

The normal readings for the settings on the iron lines follow, with the formulæ derived from them:

NORMAL READINGS FOR THE IRON LINES.

(In Revolutions for 0°C.)

Camera A		Camera B	
λ	*n*	λ	*n*
4191.611	5.245	4202.195	8.359
99.256	9.560	36.112	20.875
4204.119	12.280	50.945	26.127
10.521	15.814	60.640	29.489
19.523	20.727	71.934	33.336
22.387	22.277	82.565	36.892
33.771	28.354	94.290	40.747
36.118	29.587	99.410	42.405
38.980	31.100	4308.080	45.184
82.567	53.139	15.262	47.462
94.290	58.808	25.940	50.799
4308.081	65.338	37.216	54.260
15.255	68.693	52.908	58.986
37.219	78.709	76.108	65.763
52.910	85.665	83.720	67.935
76.104	95.653	4404.929	73.869
83.724	98.868	15.301	76.709
4404.929	107.615	27.490	79.988
15.301	111.706	47.912	85.359
27.490	116.634	59.301	88.291
		76.185	92.556
		4528.798	105.245

FORMULÆ.

Camera A.

$$\lambda = 3276.923 + \left(\frac{[4.1143394]}{871.363 - n}\right)^{\frac{1}{0.6}}$$

$$\epsilon = \pm\sqrt{\frac{\Sigma(\epsilon)^2}{m-1}} = \pm\ 0.0061 \text{ t.-m.}$$

Camera B.

$$\lambda = 3355.245 + \left(\frac{[3.7727324]}{652.237 - n}\right)^{\frac{1}{0.6}}$$

$$\epsilon = \sqrt{\frac{\Sigma(\epsilon)^2}{m-1}} = \pm\ 0.0059 \text{ t.-m.}$$

(Numbers in brackets [ ] are logarithms.)

RADIAL VELOCITY FOR A DISPLACEMENT OF I MICROMETER DIVISION.

CAMERA A		CAMERA B	
λ	Velocity	λ	Velocity
4190	1.26 km	4200	1.87 km
4250	1.37	4250	2.02
4300	1.47	4300	2.16
4350	1.57	4350	2.37
4400	1.67	4400	2.46
4430	1.71	4450	2.60
		4500	2.74
		4550	2.90

All computations were made in duplicate.

To convince myself of the power of the new spectrograph, I have a few times photographed, on the same plate, the spectrum of the east and west limbs of the Sun at extremities of the equator. The spectrum of the center of the disk could also be taken, by a special attachment, on the same plate. The solar rotation can be determined from such plates. Lantern slide plates of Thomas were used. I obtained the following results from two plates taken on June 13, 1902:

LINE	FIRST PLATE		SECOND PLATE	
	Relative Displacement	Velocity of Solar Equator	Relative Displacement	Velocity of Solar Equator
	p		*p*	
λ 4233.8	2.7	1.80 km	2.9	1.87 km
27.6	3.0	1.98	3.0	1.92
22.4	3.0	1.97	2.5	1.57
15.7	2.8	1.81	2.9	1.82
10.5	3.5	2.28	3.0	1.87
04.1	2.4	1.53	3.7	2.30
02.2	3.9	2.48	2.3	1.40
4199.2	3.3	2.09	2.6	1.58
95.6	3.9	2.46	3.2	1.91
91.6	2.7	1.69	3.0	1.88
87.2	2.4	1.49	3.0	1.87
85.1	2.9	1.80	3.4	2.11
81.9	1.9	1.17	3.5	2.16
77.8	2.0	1.23	2.4	1.47
75.0	3.7	2.25	3.2	1.95
71.1	2.8	1.70	2.5	1.52
67.4	3.6	2.18	3.5	2.11
58.9	2.6	1.56	2.8	1.67
57.0	2.5	1.48	3.2	1.90
55.0	3.3	1.92	3.9	2.31
4144.0	3.2	1.85	2.7	1.57
	Mean	1.84 ± 0.09 km		1.84 ± 0.063 km

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Object	Camera	Date—Gr. M. T.	Duration	Hour Angle	Slit-Width	Comparison Spectrum	Temperature		Remarks
							Beginning	End	
		1902	m	h m		s	°		
a Persei . . .	B	Oct. 25.409	51	E 1 15	17	*Fe* 6 Mid.	+2.2C	+2.2C	
	B	26.373	30	E 2 5	18	" 10	−1.5	−1.5	
	B	31.417	32	E 0 40	18	" 9	+4.0	+4.0	
	B	Nov. 6.371	30	E 0 23	18	" 10	−2.0	−2.0	Diffuse
	B	8.379	31	E 1 2	18	" 10	−1.4	−1.4	
	B	15.413	30	W 0 13	18	" 12	−3.7	−3.7	
	A	26.314	57	E 1 27	18	" 20	−9.6	−9.6	
	A	Dec. 19.363	35	W 1 15	18	" 25	−9.8	−9.8	
		1903							
β Geminorum	A	Jan. 31.448	38	W 1 46	19	*Fe* 30	−3.5	−3.5	
	A	Feb. 13.364	42	W 0 35	18	" 30	−7.7	−7.7	
	A	22.248	43	W 0 41	18	" 20	+0.4	+0.5	
	A	24.233	48	E 1 52	18	" 30	−0.7	. . . . . .	
	A	Mar. 2.424	49	W 3 9	19	" 30	+1.1	+1.1	
	A	3.383	28	W 2 14	19	" 3	+0.5	+0.5	No gr. gl.; w'k
	A	13.380	40	W 1 49	19	" 30	+1.0	+1.0	Wedge toward violet
	A	14.331	42	W 1 40	18	" 30	−2.7	. . . . . .	
	A	21.377	41	W 3 17	18	" 2	−1.8	−1.75	No ground gl.
		1903							
a Boötis	A	Apr. 15.393	22	E 1 14	15	*Fe* 30	+3.3	. . . . . .	Camera below
	A	17.420	44	E 0 28	12	" 35	+2.3	+2.3	"
	A	21.397	40	E 0 45	16	" 35	+4.0	+4.0	"
	A	May 8.366	58	E 0 28	16	" 30	+5.5	+5.5	"
	A	9.369	50	E 0 15	16	" 30	+2.8	+2.8	Camera above
	A	16.340	48	E 0 29	17	" 25	+8.1	+8.1	"
	A	17.352	55	E 0 7	16	" ?	+7.7	+7.7	
	B	27.352	43	W 0 31	14	" 10	+11.6	+11.6	Camera below
	B	July 21.334	28	W 3 52	15	" 9	+11.0	+11.0	"
		1902							
γ Aquilae . .	B	Aug. 5.368	66	E 0 5	15	*Fe* and *H* 60	+14.4	+14.0	
	B	7.327	62	E 0 53	17	" 60	+14.3	+14.6	Poor
	B	13.359	97	W 0 19	16	" 60	+12.6	+12.6	
	B	15.325	70	E 0 21	16	" 60	+10.6	+10.6	
	B	18.361	66	W 0 42	16	" 60	+12.5	+12.4	
	B	19.359	60	E 0 38	15	" 60	+13.5	+13.3	Image good
	B	26.327	30	W 0 18	16	" 60	+11.0	+11.0	Faint
		1903							
	B	July 21.382	61	E 0 39	15	*Fe* 9	+11.0	+11.0	Faint
	B	28.423	66	W 0 45	15	" 9	+15.8	+15.8	
	B	Aug. 7.383	60	W 0 29	20	" 9	+13.2	+13.3	
		1902							
ε Pegasi	B	Aug. 19.408	65	E 0 2	15	*Fe* and *H* 60	+13.3	+13.3	Poor
	B	Sept. 10.326	60	E 0 34	18	" 60	+9.3	+9.5	
	B	11.316	60	E 0 49	18	" 60	+8.5	+8.5	
		1903							
	B	Aug. 7.430	67	E 0 13	20	*Fe* 9	+13.3	+13.3	
	B	10.397	73	E 0 54	20	" 10	+10.0	+10.0	
	B	19.417	62	W 0 10	20	" 10	+11.5	+11.5	
	B	27.438	60	W 0 11	20	" 15	+9.4	+9.4	Objective half-covered
		1903							
γ Cephei . . .	B	Sept. 3.426	72	E 0 35	20	*Fe* 10	+11.2	+11.2	
	B	7.393	71	E 1 7	20	" 12	+14.3	+14.3	
	B	8.375	81	E 1 30	20	" 10	+12.4	. . . . . .	
	B	13.383	75	E 0 57	20	" 12	+9.3	9.3	Cloudy; weak
		1903							
Jupiter	B	Sept. 15.404	50	E 0 2	16	*Fe* 6	+9.5	+9.5	Camera above
	B	17.397	48	E 0 3	17	" 5	+11.1	+11.1	"
	B	18.396	41	0 0	17	" 5	+11.5	+11.5	"
	B	19.393	48	W 0 1	17	" 5	+10.5	+10.7	"
	B	21.413	47	W 0 38	17	" 5	+11.0	+11.0	Camera below
	B	22.305	49	W 0 18	17	" 5	+10.3	+10.3	"
	B	23.384	42	W 0 6	17	" 5	+9.9	+9.9	"
	B	23.422	60	W 0 58	17	" 5	+9.9	+9.8	"
		1903							
Mars	A	Mar. 29.389	36	E 0 47	14	*Fe* 30	+4.7	+4.7	Camera below
	A	29.420	40	E 0 3	14	" 35	+4.7	+4.7	"
	A	30.389	34	E 0 42	14	" 30	+3.2	+3.2	"
	A	Apr. 13.352	34	E 0 21	13	" 30	+9.5	+9.5	"
	A	14.360	41	E 0 5	12.5	" 35	+5.0	+5.0	"
	A	15.357	60	E 0 5	12.5	" 35	+3.4	+3.2	"
	A	17.377	59	W 0 36	12	" 35	+2.3	+2.3	"

The planets *Mars*, *Venus*, and *Jupiter* were also observed and the results compared with the radial velocities deduced from the data in the Nautical Almanac. I give here the determinations for *Mars* and *Jupiter* only, as the plates of *Venus* constitute a large mass of material and will be specially discussed. I must state that in case of the planets my settings were made on the two edges of the spectra, and then the means were taken. It was very important in the case of *Jupiter* to hold the slit at the same point, as the rapid rotation may otherwise affect the results.

On combining the results given below the radial velocities show a worse agreement than would have been expected *a priori* with such an instrument. It may be that the method of reduction is not sufficiently rigorous, particularly in case of *a Boötis*, the spectrograms of which were taken with the wedge *under* the plate-holder, in a different position from that for the other stars. I am convinced that the second series of observations of the standard velocity stars will give better accordance than the present series.

Greenwich Mean Time is used throughout in this article.

MARS.

1903, March 29.389 G. M. T.

Solar Wave-Length	Velocity
4274.958	−1.96km
4307.017	3.00
15.209	0.84
52.030	2.75
59.784	2.75
4408.622	1.02

No. of comp. lines 7
V_d +0.04
Mean −2.06
Computed vel. −1.81

MARS.

1903, March 29.420.

Solar Wave Length	Velocity
4292.200	−2.03km
94.273	1.96
4307.017	4.32
15.209	3.89
20.207	1.80
52.083	0.28
52.908	0.14
59.784	1.79
4408.622	2.38
15.203	4.82
16.074	1.83
27.482	3.72

No. of comp. lines 9
V_d 0.00
Mean −2.41
Computed vel. −1.84

MARS.

1903, March 30.389.

Solar Wave-Length	Velocity
4204.273	−1.75
4315.262	1.95
40.634	0.41
52.007	0.62
4408.582	1.70
15.203	0.75
27.420	1.42

No. of comp. lines 7
V_d +0.04
Mean −1.23
Computed vel. −1.44

MARS.

1203, April 13.352.

4352.007	+2.07
71.368	3.64
4404.927	5.41
08.582	3.06
15.293	4.68
27.420	3.86

No. of comp. lines 7
V_d +0.02
Mean +3.74
Computed vel. +3.73

1903, April 14.360.

4294.301	+3.63
4306.937	2.44
15.138	4.51
52.007	3.44
83.720	4.72
95.286	3.62
4408.622	2.38
27.482	2.30

No. of comp. lines 6
V_d 0.00
Mean +3.38
Computed vel. +4.05

1903. April 15.357.

4294.273	+4.89
4306.858	5.85
15.138	5.00
25.039	4.30
40.634	5.11
51.030	7.57
59.784	−0.08
4408.582	+3.53
27.420	3.46

No. of comp. lines 7
V_d 0.00
Mean +4.33
Computed vel. +4.30

MARS.

1903. April 17.377.

4294.273	+4.26
4306.858	9.04
15.138	7.71
52.007	5.30
52.908	6.75
59.784	1.99
4404.927	3.88
08.622	5.37
27.482	4.00

No. of comp. lines 6
V_d +0.03
Mean +5.37
Computed vel. +4.97

JUPITER.

1903, Sept. 15.404.

Solar Wave-Length	Velocity
4237.240	+3.82
45.455	2.05
54.505	6.97
67.985	4.50
74.958	3.93
88.230	2.24
95.289	0.21
4352.083	0.96
59.784	4.13
71.442	2.06
95.286	4.98

No. of comp. lines 11
V_d 0.00
Mean +3.26
Computed vel. +2.09

JUPITER.

1903, Sept. 17.397.

Solar Wave-Length	Velocity
4229.868	+4.26
37.334	0.56
43.608	2.54
45.520	2.12
46.996	5.72
54.505	7.96
74.958	3.79
91.545	1.82
4320.992	2.92
52.083	6.27
71.442	5.15
95.286	2.91

No. of comp. lines 13
V_d 0.00
Mean +3.84
Computed vel. +3.11

1903, Sept. 18.396.

Solar Wave-Length	Velocity
4254.505	+2.89
74.958	1.68
92.320	1.96
4340.634	5.74
52.083	5.37
69.941	6.45
71.442	4.66
4401.613	3.00
27.482	1.15

No. of comp. lines 12
V_d 0.00
Mean +3.65
Computed vel. +3.03

JUPITER.

1903, Sept. 19.393.

4210.491	+3.63
19.484	1.56
49.952	3.47
45.422	6.78
60.581	4.44
74.911	3.93
91.276	1.61
4315.209	1.17
71.368	5.28
4402.575	4.70

No. of comp. lines 11
V_d 0.00
Mean +3.66
Computed vel. +4.15

1903, Sept. 21.413.

4222.382	+7.52
37.240	5.03
45.422	8.19
54.505	7.33
74.958	7.93
91.276	5.03
4315.262	5.01
52.083	3.93
59.784	5.64
67.955	4.48
79.941	5.01
95.285	3.82

No. of comp. lines 10
V_d −0.03
Mean +5.74
Computed vel. +5.19

JUPITER.

1903, Sept. 22.395.

4210.561	+2.49
15.703	5.90
22.382	5.60
37.314	2.76
40.014	4.46
43.608	3.39
54.505	7.75
74.958	5.82
92.290	5.73
4303.669	5.85
15.209	5.42
52.083	3.93
59.809	8.06
71.442	6.11
4427.482	6.10

No. of comp. lines 14
V_d 0.00
Mean +5.29
Computed vel. +5.69

1903, Sept. 23.384.

4243.442	+5.30
54.505	2.89
74.911	2.88
88.149	6.84
92.290	4.05
4318.817	3.82
40.634	3.73
52.007	6.06
59.784	7.42
71.368	5.76
94.943	4.97

No. of comp. lines 10
V_d 0.00
Mean +4.88
Computed vel. +6.20

JUPITER.

1903, Sept. 23.422.

4247.591	+7.91
54.505	4.84
74.958	5.19
91.276	4.38
4315.209	5.42
18.817	7.56
40.634	7.73
52.007	5.03
59.784	9.15
71.368	6.48
95.285	5.53
4408.622	6.66
27.420	8.66

No. of comp. lines 12
V_d −0.06
Mean +6.50
Computed vel. +6.23

SUMMARY.

MARS		*JUPITER*	
Date	Comp. Obs.	Date	Comp. Obs.
March 29.....	+0.21	Sept. 15....	−1.17
29.....	+0.57	17....	−0.73
30.....	−0.25	18....	−0.02
April 13.....	+0.01	19....	+0.40
14.....	+0.67	21....	−0.52
15.....	+0.03	22....	+0.40
17.....	−0.43	23....	+1.32
		23....	−0.21
Mean......	+0.12 km	Mean....	−0.06 km

a PERSEI.

1902, Oct. 25.409. Hour angle E 1h 15m.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4202.198	− 8.84	4320.992	−15.82
36.112	17.91	52.007	19.70
50.945	15.38	74.775	10.90
54.505	13.53	76.107	12.61
60.551	17.17	83.720	17.44
94.273	17.73	4404.927	17.02
4308.081	16.51	50.654	15.50
14.381	18.21	64.731	15.50
No. of comp.		Mean	−15.61
lines	14	V_a	+12.27
ϵ	±2.8	V_d	+ 0.06
ϵ_0	±0.7	C	− 0.30
		Rad. vel.	− 3.58

1902, Oct. 26.313. Hour angle E 2h 5m.

4202.198	− 8.49	4314.381	−16.61
15.703	14.59	20.902	12.00
26.904	17.10	52.007	12.55
36.112	18.90	76.107	9.51
50.945	17.00	83.720	12.11
54.505	14.18	95.201	12.35
58.389	15.30	4404.927	12.87
94.301	12.57	64.731	14.44
99.296	12.88	81.438	14.59
4308.081	13.02	4522.974	16.84
No. of comp.		Mean	−13.90
lines	14	V_a	+11.89
ϵ	±2.6	V_d	+ 0.10
ϵ_0	±0.6	C	− 0.30
		Rad. vel.	− 2.21

1902, Oct. 31.417.

4215.703	−14.80	4320.902	−13.11
36.112	12.18	25.039	14.21
50.945	13.76	51.030	13.23
54.505	13.53	74.775	12.58
71.934	12.43	76.107	9.51
88.075	10.35	83.720	15.26
94.273	14.73	4404.927	13.82
4308.081	14.48	61.617	10.61
14.281	10.50	76.185	11.48
15.209	14.55	4508.027	13.63
No. of comp.		Mean	−12.98
lines	13	V_a	+ 9.75
ϵ	±1.7	V_d	+ 0.05
ϵ_0	±0.4	C	− 0.30
		Rad. vel.	− 3.48

a PERSEI.

1902, Nov. 6.371. Hour angle E 0h 23m.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4250.945	− 9.74	4320.992	− 7.77
54.505	12.75	40.634	7.05
58.389	12.40	52.007	10.20
71.945	8.63	67.955	11.32
74.958	8.98	83.720	10.94
94.273	11.52	4404.027	13.07
4308.081	11.48	62.897	10.08
13.034	10.85	4501.448	9.46
14.381	11.53		
No. of comp.		Mean	−10.46
lines	13	V_a	+ 7.33
ϵ	±1.7	V_d	+ 0.01
ϵ_0	±0.4	C	− 0.30
		Rad. vel.	− 3.42

1902, Nov. 8.379. Hour angle E 1h 2m.

4215.703	− 8.46	4308.081	−10.37
26.704	11.28	14.381	11.33
27.606	14.12	44.597	9.80
36.112	14.58	52.007	9.03
50.945	8.75	83.720	9.04
58.389	12.26	4404.927	6.94
99.296	8.78	81.438	8.36
No. of comp.		Mean	−10.22
lines	13	V_a	+ 6.46
ϵ	±2.2	V_d	+ 0.03
ϵ_0	±0.6	C	− 0.30
		Rad. vel.	− 4.03

1902, Nov. 15.413. Hour angle W 0h 13m.

4215.703	− 7.92	4308.081	−8.00
22.875	10.15	14.381	8.69
50.945	7.33	20.992	2.92
54.505	6.27	52.083	8.54
88.075	7.55	4404.927	3.47
4300.211	7.11	81.404	5.49
No. of comp.		Mean	−6.95
lines	14	V_a	+3.35
ϵ	±2.2	V_d	0.00
ϵ	±0.6	C	−0.30
		Rad. vel.	−3.00

α PERSEI.

1902, Nov. 26.314. **Hour angle E $1^h 27^m$.**

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4226.904	+0.21	4288.075	−1.89
46.996	0.35	4315.209	0.14
50.945	0.49	25.939	+1.39
54.505	2.33	52.007	−0.21
58.345	−1.34	95.201	+3.75
71.934	2.11	4404.927	3.74
No. of comp.		Mean	+1.21
lines	13	V_a	−1.58
ϵ	±1.6	V_d	+0.06
ϵ_0	±0.5	C	−0.07
		Rad. vel.	−0.38

1902, Dec. 19.363. **Hour angle W $1^h 15^m$.**

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4226.904	+ 8.44	4308.081	+8.13
36.112	7.64	14.381	9.52
58.389	8.38	15.209	8.40
71.945	13.90	25.921	8.73
88.075	10.76	52.007	9.99
94.273	10.40	83.720	9.85
4300.211	13.04	4404.927	9.39
No. of comp.		Mean	+ 9.68
lines	13	V_a	−11.68
ϵ	±1.7	V_d	− 0.04
ϵ_0	±0.5	C	− 0.07
		Rad. vel.	− 2.11

β GEMINORUM.

1903, Jan. 31.448. **Hour angle W $1^h 40^m$.**

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4185.058	+15.83	4246.251	+11.93
92.782	9.36	47.501	16.94
4210.523	9.33	50.959	17.07
19.580	12.43	54.505	17.27
22.382	14.78	4315.209	10.70
38.919	14.77	53.407	11.71
40.039	12.66	4404.927	14.46
45.520	11.94		
No. of comp.		Mean	+13.41
lines	19	V_a	− 9.54
ϵ	±2.7	V_d	− 0.09
ϵ_0	±0.7	C	− 0.07
		Rad. vel.	+ 3.71

β GEMINORUM.

1903, Feb. 13.364. **Hour angle W $0^h 35^m$.**

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4185.058	+22.07	4236.168	+22.38
4200.148	15.43	92.263	19.00
19.580	14.71	4314.381	18.84
22.382	20.81	15.209	15.63
36.160	15.92	40.634	21.55
40.014	20.57	52.083	17.16
45.520	15.82	52.931	20.74
46.996	20.40	58.879	19.19
47.501	20.53	69.784	20.83
50.959	18.76	4404.927	15.25
54.505	23.62	15.203	21.06
55.002	20.17	27.482	14.50
68.138	17.92		
No. of comp.		Mean	+18.91
lines	19	V_a	−15.62
ϵ	±2.7	V_d	− 0.03
ϵ_0	±0.6	C	− 0.14
		Rad. vel.	+ 3.12

1903, Feb. 22.343. **Hour angle W $0^h 41^m$.**

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4187.071	+20.05	4294.301	+25.76
4200.148	24.84	4308.081	23.58
19.580	23.16	14.381	23.09
22.382	25.32	15.262	20.50
33.772	25.20	19.030	17.07
36.160	25.62	37.414	16.42
39.107	19.80	40.634	24.40
40.014	25.10	52.718	18.46
45.520	23.01	53.044	20.46
46.996	26.12	58.870	25.18
47.501	26.20	59.784	22.21
50.287	26.53	69.041	21.47
50.959	26.53	71.442	19.62
54.505	27.49	76.107	22.47
68.138	19.67	83.720	26.13
71.958	27.36	4404.927	18.52
92.290	24.58	15.203	23.07
No. of comp.		Mean	+23.12
lines	20	V_a	−19.38
ϵ	±3.0	V_d	− 0.04
ϵ_0	±0.5	C	− 0.14
		Rad. vel.	+ 3.55

β GEMINORUM.

1903, Feb. 24.233. Hour angle E $1^h\ 52^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4185.058	+26.72	4292.450	+19.56
99.267	24.85	94.301	25.90
4200.148	21.42	4314.430	25.51
19.580	23.31	15.262	20.78
22.382	23.19	40.634	24.80
36.160	23.79	52.083	23.50
40.014	25.89	59.784	24.48
45.520	21.83	69.941	26.49
46.996	24.64	76.107	24.74
50.287	24.62	83.720	26.13
54.505	27.89	4404.927	21.45
55.134	19.59	15.293	24.25
86.168	22.80	27.482	17.81
No. of comp.		Mean	+23.69
lines	18	V_a	−20.10
ϵ	±2.5	V_d	+ 0.10
ϵ_0	±0.5	C	− 0.14
		Rad. vel.	+ 3.55

1903, March 2.424. Hour angle W $3^h\ 9^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4188.019	+25.85	4294.301	+28.63
4200.148	28.35	4314.381	27.45
19.580	25.44	15.262	20.01
36.279	21.66	55.599	25.01
39.107	24.61	53.044	23.69
40.039	28.07	59.784	28.27
47.634	27.07	71.368	24.07
74.958	29.25	4404.927	22.20
88.230	27.76	15.293	26.34
No. of comp.		Mean	+25.76
lines	20	V_a	−22.32
ϵ	±2.6	V_d	− 0.15
ϵ_0	±0.6	C	− 0.14
		Rad. vel.	+ 3.15

1903, March 3.383. Hour angle W $2^h\ 14^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4185.058	+27.86	4294.301	+28.14
4219.580	25.11	4314.381	28.70
39.107	22.13	15.138	29.53
40.014	25.53	40.634	25.23
45.520	26.27	52.007	25.78
46.996	27.32	52.931	27.35
50.959	27.23	4404.927	20.49
74.958	28.62	15.293	31.38
No. of comp.		Mean	+26.67
lines	18	V_a	−22.64
ϵ	±2.0	V_d	− 0.10
ϵ_0	±0.5	C	− 0.14
		Rad. vel.	+ 3.79

β GEMINORUM.

1903, March 13.380. Hour angle W $1^h\ 49^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4236.112	+28.25	4371.368	+29.48
37.339	25.48	4408.582	28.96
40.014	28.00	27.482	28.03
45.455	26.26	35.321	26.98
46.996	30.78	42.510	34.48
74.958	31.15	59.301	32.33
87.117	28.46	79.576	32.46
4315.138	29.12	73.031	29.43
37.216	30.97	76.214	31.33
52.007	29.41	82.438	28.96
52.931	33.12	4522.802	28.84
58.879	29.50	28.798	24.96
59.784	31.91	35.741	32.25
No. of comp.		Mean	+29.34
lines	12	V_a	−25.57
ϵ	±2.3	V_d	− 0.09
▭ ϵ_0	±0.5	C	− 0.14
		Rad. vel.	+ 3.54

1903, March 14.331. Hour angle W $1^h\ 40^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4250.945	+26.45	4359.784	+27.09
74.911	29.33	83.720	28.38
88.134	28.73	4404.927	26.56
94.204	30.73	15.293	31.78
4313.034	25.24	27.482	27.68
52.007	28.03	59.301	29.98
52.908	29.35		
No. of comp.		Mean	+28.41
lines	14	V_a	−25.81
ϵ	±1.8	V_d	− 0.09
ϵ_0	±0.5	C	− 0.14
		Rad. vel.	+ 2.37

1903, March 21.377. Hour angle W $3^h\ 17^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4237.339	+32.05	4371.368	+31.00
40.014	31.68	76.107	30.02
50.959	33.86	4408.622	27.88
54.505	33.96	27.482	32.50
74.958	30.60	35.184	34.14
88.149	31.88	47.892	31.55
92.370	28.98	79.545	30.72
93.957	27.94	73.031	29.57
40.634	30.60	76.185	31.82
52.931	33.76	94.738	28.95
No. of comp.		Mean	+31.17
lines	17	V_a	−27.35
ϵ	±1.9	V_d	− 0.16
ϵ_0	±0.4	C	− 0.14
		Rad. vel.	+ 3.52

α *BOÖTIS.*

1903, April 15.393. Hour angle E 1h 14m.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4236.112	−7.29	4294.272	−8.10
39.952	6.29	4315.121	5.63
45.455	5.86	40.634	8.15
50.945	7.47	52.007	4.55
54.505	7.89	52.931	4.13
74.958	7.08	4408.582	4.35
89.885	6.22	27.482	6.15

No. of comp. lines	17	Mean	−6.37
ϵ	±1.4	V_a	−0.41
ϵ_0	±0.4	V_d	+0.07
		C	−0.14
		Rad. vel.	−6.85

1903, April 17.420. Hour angle E 0h 28m.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4202.198	−6.99	4294.272	−5.87
19.516	3.27	4315.005	4.31
36.112	6.94	40.634	6.36
74.958	6.87	52.007	5.86
89.885	6.49	4427.482	8.19

No. of comp. lines	15	Mean	−6.12
ϵ	±1.4	V_a	−1.29
ϵ_0	±0.4	V_d	+0.03
		C	−0.14
		Rad. vel.	−7.52

1903, April 21.397. Hour angle E 0h 45m.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4219.516	−1.85	4315.138	−2.04
36.112	1.42	39.731	3.66
39.975	1.98	52.007	0.83
45.455	1.62	52.908	2.83
46.996	2.54	71.368	2.20
50.945	0.35	4404.027	2.50
54.505	1.69	08.021	3.54
74.958	2.81	27.482	2.24
94.301	2.86		

No. of comp. lines	23	Mean	−2.08
ϵ	±0.9	V_a	−3.01
ϵ_0	±0.2	V_d	+0.04
		C	−0.41
		Rad. vel.	−5.46

α *BOÖTIS.*

1903, May 8.366. Hour angle E 0h 28m.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4337.216	+3.32	4427.482	+6.16
52.931	7.43	40.429	4.80
95.286	6.75	49.569	2.90
4408.683	4.90	4528.647	4.17

No. of comp. lines	10	Mean	+ 5.05
ϵ	±1.7	V_a	−10.31
ϵ_0	±0.4	V_d	+ 0.02
		C	− 0.41
		Rad. vel.	− 5.65

1903, May 9.369. Hour angle E 0h 15m.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4287.566	+6.78	4327.082	+7.00
88.149	5.53	52.908	7.65
94.204	4.54	59.784	3.24
4315.121	4.31	78.419	2.12

No. of comp. lines		Mean	+ 5.15
ϵ	±1.7	V_a	−10.44
ϵ_0	±0.4	V_d	+ 0.02
		C	− 0.44
		Rad. vel.	− 5.71

1903, May 16.340. Hour angle E 0h 29m.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4206.862	+5.20	4315.005	+5.14
19.580	5.18	27.082	7.00
22.382	6.66	40.634	4.49
40.039	5.52	52.007	7.96
46.996	5.86	53.044	3.17
74.058	7.29	59.784	8.51
94.273	6.29	71.368	8.35
4314.381	4.38	4404.027	6.87

No. of comp. lines	17	Mean	+ 6.12
ϵ	±1.5	V_a	−13.08
ϵ	0.4	V_d	+ 0.03
		C	− 0.41
		Rad. vel.	− 7.34

α BOÖTIS.

1903, May 17.352. Hour angle E $0^h 7^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4206.862	+7.34	4246.998	+8.32
22.381	7.74	50.945	8.18
35.389	8.49	4315.138	6.32
40.014	6.92		

No. of comp.		Mean	+7.61
lines	10	V_a	−13.45
ϵ	±0.9	V_d	0
ϵ_0	±0.4	C	−0.41
		Rad. vel.	−6.25

1903, May 27.352. Hour angle W $0^h 31^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4198.494	+17.63	4294.273	+13.20
4200.148	13.71	15.138	14.04
02.198	15.12	25.039	16.42
36.112	14.09	52.007	16.12
50.945	15.30	52.935	17.97
54.505	14.87	4404.927	12.32
74.958	14.17	27.482	12.80

No. of comp.		Mean	+14.84
lines	12	V_a	−16.84
ϵ	±1.6	V_d	−0.03
ϵ_0	±0.4	C	−2.21
		Rad. vel.	−4.24

1903, July 21.334. Hour angle W $3^h 52^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4198.494	+18.14	4352.007	+20.53
4236.112	15.44	52.935	23.36
54.505	17.68	83.720	19.90
54.012	18.54	4404.927	19.74
94.273	17.45	27.482	21.47
4314.064	22.23		

No. of comp.		Mean	+19.59
lines	12	V_a	−25.05
ϵ	±2.3	V_d	−0.19
ϵ	±0.7	C	−0.55
		Rad. vel.	−6.20

γ AQUILAE.

1902, Aug. 5.368. Hour angle E $0^h 5^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4252.917	+5.15	4369.941	+2.67
60.151	2.1[illegible]	91.924	4.10
72.114	3.54	95.201	3.21
4339.584	2.56	4415.293	6.32
52.908	5.03	27.420	4.61
63.330	8.93	82.438	1.94

No. of comp.		Mean	+4.19
lines	10	V_a	−5.80
ϵ	±2.0	V_d	+0.03
ϵ_0	±0.6	C	−0.30
		Rad. vel.	−1.81

1902, Aug. 7.327. Hour angle E $0^h 53^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4236.112	+ 6.30	4395.286	+11.40
58.639	5.28	4412.415	11.76
74.958	11.08	03.042	10.24
94.273	7.33	30.582	3.39
4319.030	6.32	73.031	9.04
20.992	8.40	94.548	7.66
39.882	6.42	4522.802	5.04
71.308	7.75		

No. of comp.		Mean	+7.83
lines	9	V_a	−6.61
ϵ	±2.3	V_d	+0.05
ϵ_0	±0.6	C	−0.30
		Rad. vel.	+0.05

1902, Aug. 13.359. Hour angle W $0^h 19^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4200.735	+ 7.88	4333.925	+10.10
45.422	2.83	39.617	7.32
58.477	9.15	52.876	4.89
74.746	11.92	59.054	10.52
85.966	7.62	71.308	3.57
94.204	5.72	91.874	7.24
4320.318	10.13	95.201	9.28
32.867	3.81	4427.420	4.34

No. of comp.		Mean	+7.27
lines	12	V_a	−9.06
ϵ	±2.8	V_d	−0.02
ϵ	±0.7	C	−0.30
		Rad. vel.	−2.11

γ AQUILAE.

1902, Aug. 15.325. **Hour angle E $0^{h}\ 21^{m}$.**

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4274.958	+ 6.66	4369.941	+ 8.85
88.149	5.73	71.368	3.84
91.630	9.08	95.286	10.91
92.208	9.35	4404.927	8.37
4314.381	6.74	08.495	7.07
20.992	6.24	12.293	5.57
32.867	8.02	15.293	8.08
34.063	8.23	25.827	6.78
39.731	6.97	94.356	6.54
44.597	6.97	4522.691	10.14
52.931	10.22	31.327	9.86
59.784	9.22		

No. of comp.		Mean	+7.36
lines	5	V_a	−9.84
ϵ	±1.8	V_d	+0.02
ϵ_c	±0.4	C	−0.30
		Rad. vel.	2.76

1902, Aug. 18.361. Hour angle W $0^{h}\ 42^{m}$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4249.890	+ 9.26	4352.908	+11.78
58.477	8.10	79.373	6.51
67.985	11.31	95.286	6.21
94.273	8.11	4412.297	6.52
4314.321	9.10	25.827	8.13
34.063	8.58	82.388	10.17
35.034	7.05	94.452	11.67
39.731	7.66		

No. of comp.		Mean	+ 8.68
lines	14	V_a	−11.02
ϵ	±1.9	V_d	− 0.03
ϵ_0	±0.5	C	− 0.30
		Rad. vel.	− 2.07

1902, Aug. 19.359. Hour angle E $0^{h}\ 38^{m}$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4239.952	+ 8.83	4373.396	+ 9.24
58.510	9.02	95.201	10.10
86.101	7.76	4404.027	10.14
4314.964	10.08	25.879	7.05
20.907	8.12	27.266	14.77
32.867	8.71	30.311	7.17
34.119	7.95	35.321	6.76
39.731	7.67	66.711	6.64
44.597	8.08	69.316	12.33
51.930	8.50	82.338	7.56
55.320	15.29	94.520	7.61

No. of comp.		Mean	+ 9.06
lines	13	V_a	−11.40
ϵ	±2.3	V_d	+ 0.03
ϵ_0	±0.5	C	− 0.30
		Rad. vel.	− 2.61

γ AQUILAE.

1902, Aug. 26.327. **Hour angle W $0^{h}\ 18^{m}$.**

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4320.907	+ 7.00	4371.368	+ 8.37
28.080	14.00	79.396	11.64
32.867	11.42	4412.415	9.04
33.971	16.12	25.931	12.12
39.731	12.01	27.482	9.14
44.451	15.18		

No. of comp.		Mean	+11.46
lines	12	V_a	−14.00
ϵ	±2.8	V_d	+ 0.02
ϵ_c	±0.9	C	− 0.30
		Rad. vel.	− 2.82

1903, July 21.382. Hour angle E $0^{h}\ 39^{m}$.

4334.063	+0.35	4425.031	−4.81
71.368	−4.73	27.482	5.96
4412.203	1.43	30.356	0.27
22.085	1.15	72.884	2.48
24.457	4.20		

No. of comp.		Mean	−2.74
lines	20	V_a	+0.62
ϵ	±2.2	V_d	+0.04
ϵ_c	±0.7	C	−0.55
		Rad. vel.	2.63

1903, July 28.423. Hour angle W $0^{h}\ 45^{m}$.

4332.867	+ 1.35	4412.203	+ 1.56
34.110	0.76	25.827	0.47
52.008	3.17	66.727	5.30
71.368	0.07	72.058	2.47

No. of comp.		Mean	+ 1.89
lines	22	V_a	2.36
ϵ	±1.7	V_d	− 0.04
ϵ_0	±0.6	C	0.55
		Rad. vel.	1.11

1903, Aug. 7.383. Hour angle W $0^{h}\ 29^{m}$.

4245.520	+ 1.76	4412.203	+ 7.07
4315.209	4.10	25.031	4.00
34.130	5.83	27.420	4.27
71.368	6.45	72.012	7.44
95.286	4.56		

No. of comp.		Mean	+ 4.03
lines	20	V_a	−6.54
ϵ	±1.8	V_d	− 0.03
ϵ	±0.6	C	−0.55
		Rad. vel.	−2.19

ϵ *PEGASI.*

1902, Aug. 19.408. Hour angle E $0^h\ 2^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4200.045	+3.50	4344.451	+8.28
19.484	3.06	52.908	8.27
39.952	2.90	58.722	4.54
50.287	5.78	71.368	7.75
54.391	7.60	4404.927	0.27
74.888	5.96	15.293	2.78
82.565	4.75	25.827	4.27
94.273	2.44	27.420	5.89
4305.916	4.18	30.356	4.40
08.081	2.72	61.818	5.90
15.090	2.43	94.452	2.87
20.907	5.00	4522.691	3.91
34.120	2.21	31.052	3.57
37.216	3.25		

No. of comp.
lines 11
ϵ ±2.0
ϵ_0 ±0.3

Mean	+4.39
V_a	+1.85
V_d	0.00
C	−0.30
Rad. vel.	+5.94

1902, Sept. 10.326. Hour angle E $0^h\ 34^m$.

4219.516	+16.06	4398.217	+14.60
20.509	13.34	4415.293	17.12
43.714	13.07	22.985	14.24
54.505	18.67	25.179	15.17
60.640	17.75	27.482	17.67
64.310	13.43	30.356	18.95
4318.817	19.08	64.875	15.85
20.992	12.43	66.727	15.70
32.980	13.77	71.571	15.83
34.120	10.38	72.884	13.88
52.908	13.85	94.548	15.14
71.368	11.39	4522.802	14.05
92.034	10.91		

No. of comp.
lines 14
ϵ ±2.4
ϵ_0 ±0.5

Mean	+14.85
V_a	− 8.23
V_d	+ 0.03
C	− 0.30
Rad. vel.	+ 6.35

ϵ *PEGASI.*

1902, Sept. 11.313. Hour angle E $0^h\ 49^m$.

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4200.129	+13.07	4366.749	+16.48
19.516	13.50	71.368	12.35
29.803	14.53	4400.738	13.63
36.112	10.76	15.293	19.84
50.945	12.48	23.060	14.44
58.477	15.42	94.548	18.48
88.149	15.11	96.676	14.94
4314.430	13.20	4522.871	15.98
25.959	18.23	31.123	14.56
39.416	14.65		

No. of comp.
lines 12
ϵ ±2.3
ϵ_0 ±0.5

Mean	+14.82
V_a	− 8.67
V_d	+ 0.05
C	− 0.30
Rad. vel.	+ 5.90

1903, Aug. 7.430. Hour angle E $0^h\ 13^m$.

4219.516	−1.19	4412.347	−2.85
46.996	1.56	25.827	+0.47
4332.938	3.18	27.420	0.00
34.120	3.18	66.727	0.81
52.921	+1.58	72.884	−3.02
71.368	−2.54	4528.798	1.39

No. of comp.
lines 20
ϵ ±1.6
ϵ_0 ±0.5

Mean	−1.34
V_a	+7.40
V_d	+0.01
C	−0.30
Rad. vel.	+5.77

1903, Aug. 10 307. Hour angle E $0^h\ 54^m$.

4318.960	−2.77	4412.347	−2.11
20.992	2.22	22.985	+0.88
34.120	1.80	25.827	0.68
52.923	+4.27	27.482	−1.15
71.368	−1.58	94.602	+1.33
74.002	+0.62		

No. of comp.
lines 20
ϵ ±2.1
ϵ_0 ±0.6

Mean	−0.33
V_a	+6.08
V_d	+0.03
C	−0.55
Rad. vel.	+5.23

ε PEGASI.

1903, Aug. 19.417. **Hour angle W $0^h\ 10^m$.**

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4219.516	+3.91	4379.396	+3.28
58.477	7.11	4412.347	6.38
4318.873	7.22	25.879	4.27
32.867	4.64	27.482	2.44
34.120	2.70	45.641	4.32
52.923	8.61	66.727	8.53
71.368	3.16	72.912	5.56
76.107	5.75		

No. of comp.		Mean	+5.19
lines	20	V_a	+1.97
ϵ	±2.0	V_d	−0.01
ϵ_0	±0.5	C	−0.55
		Rad. vel.	+6.60

1903, Aug. 27.438. **Hour angle W $0^h\ 11^m$.**

4219.483	+ 7.25	4412.297	+ 9.12
4318.960	5.41	25.879	8.54
44.591	10.14	27.420	7.93
52.923	9.58	66.727	10.87
71.442	6.90	72.884	8.72
4401.613	7.97	4522.802	9.80

No. of comp.		Mean	+8.52
lines	20	V_a	−1.82
ϵ	±1.5	V_d	−0.01
ϵ_0	±0.4	C	−0.55
		Rad. vel.	+6.14

γ CEPHEI.

1903, Sept. 3.426. Hour angle E $0^h\ 35^m$

4220.330	−52.94	4352.008	−49.05
37.240	54.30	59.784	52.35
94.273	51.83	4415.293	42.01
4315.138	50.30	27.420	47.00
52.007	50.52		

No. of comp.		Mean	−49.07
lines	20	V_a	+12.35
ϵ	±3.6	V_d	+ 0.01
ϵ_0	±1.2	C	0.55
		Rad. vel.	−38.10

γ CEPHEI.

1903, Sept. 7.393. **Hour angle E $1^h\ 7^m$.**

Solar Wave-L'gth	Velocity	Solar Wave-L'gth	Velocity
4236.112	−54.72	4315.138	−52.26
47.591	54.94	52.007	53.01
50.945	52.07	52.908	47.82
68.016	50.58	4415.293	50.46
94.273	53.57	27.420	55.29

No. of comp.		Mean	−52.47
lines	20	V_a	+12.15
ϵ	±2.2	V_d	+ 0.01
ϵ_0	±0.7	C	− 0.55
		Rad. vel.	−40.88

1903, Sept. 8.375. Hour angle E $1^h\ 30^m$.

4236.112	−54.44	4352.083	−52.24
39.952	52.34	52.908	51.47
45.455	52.35	60.801	51.02
92.200	54.30	71.368	52.14
94.273	52.46	4425.827	47.72
4315.138	49.69	27.420	51.22
40.034	51.75	54.953	53.71

No. of comp.		Mean	−51.92
lines	16	V_a	+12.10
ϵ	±1.8	V_d	+ 0.02
ϵ_0	±0.5	C	− 0.55
		Rad. vel.	−40.35

1903, Sept. 13.383. Hour angle E $0^h\ 57^m$.

4425.827	−48.65	4770.185	−50.19
54.953	52.84	4522.871	50.05
66.727	50.60	25.314	54.09
73.951	52.17	36.158	53.89

No. of comp.		Mean	−51.57
lines	17	V_a	+11.75
ϵ	±2.0	V_d	+ 0.01
ϵ_0	±0.7	C	0.55
		Rad. vel.	−40.36

SUMMARY OF RESULTS.

a Persei	
1902	
Oct. 25	−3.58 km
26	2.21
31	3.48
Nov. 6	3.42
8	4.03
15	3.90
26	0.38
Dec. 19	2.11
1902.86	−2.89 ± 0.4 km

a Boötis	
1903	
April 15	−6.58 km
17	7.52
21	5.46
May 8	5.65
9	5.71
16	7.34
17	6.25
27	4.24
July 21	6.20
1903.36	−6.07 ± 0.4 km

ε Pegasi	
1902	
Aug. 19	+5.94 km
Sept. 10	6.35
11	5.90
1903	
Aug. 7	5.77
10	5.23
19	6.60
27	6.14
1903.24	+5.99 ± 0.2 km

β Geminorum	
1903	
Jan. 31	+3.71
Feb. 13	3.12
22	3.55
24	3.55
Mar. 2	3.15
3	3.79
13	3.54
14	2.37
21	3.52
1903.16	+3.37 ± 0.1 km

γ Aquilae	
1902	
Aug. 5	−1.81
7	+0.95
13	−2.11
15	2.76
18	2.67
19	2.61
26	2.82
1903	
July 21	2.63
28	1.11
Aug. 7	2.19
1902.91	−1.08 ± 0.4 km

γ Cephei	
1903	
Sept. 3	−38.16
7	40.88
8	40.35
13	40.36
1903.68	−39.94 ± 0.6 km

Earlier determinations at Pulkowa of the velocity of γ *Cephei* were as follows:

1897, September	9	−51.9 km
	10	50.4
	11	49.8
1898, August	24	47.4

If a different choice had been made of the wave-lengths from Rowland's table, the following differing values of the radial velocities would have been obtained for three of the stars:

β Geminorum	+ 5.37 km
a Boötis	− 5.25
γ Cephei	−37.90

The following table gives the wave-lengths of the lines in the stellar spectra, corrected only for the Earth's motion. *n* denotes the number of spectrograms on which the particular line was measured:

α *PERSEI.*

λ	n	λ	n	λ	n
4202.226	5	4294.228	5	4374.816	2
15.650	4	99.270	2	76.116	3
26.825	6	4300.209	3	83.672	6
36.024	5	08.022	7	95.211	2
46.998	2	14.306	7	4404.895	8
50.893	8	15.160	3	50.673	3
54.479	7	20.962	4	64.657	3
58.328	5	25.894	3	81.409	3
71.920	5	40.654	2	4501.462	3
88.068	2	51.957	8	22.885	2

β *GEMINORUM.*

λ	n	λ	n	λ	n
4185.144	6	4254.598	7	4359.847	6
88.010	2	68.153	2	70.004	2
99.354	3	75.050	2	71.415	5
4200.185	5	86.231	2	76.158	3
19.611	7	88.192	2	83.796	3
22.448	5	92.373	2	4404.934	8
36.223	5	94.353	4	08.628	2
37.369	2	4314.454	5	15.386	8
39.112	4	15.230	5	27.500	5
40.077	10	37.335	2	35.314	2
45.550	7	40.700	7	59.381	2
47.063	5	52.092	7	69.635	2
47.686	6	53.011	8	73.094	2
50.353	3	58.944	3	73.273	2
51.028	8				

α *BOÖTIS.*

λ	n	λ	n	λ	n
4198.455	2	4250.888	5	4351.038	6
4202.131	2	54.435	5	52.802	8
06.787	2	74.800	6	59.600	2
19.449	4	89.775	2	71.287	2
22.289	2	94.169	7	83.677	3
36.017	5	4315.014	8	4404.860	6
39.897	4	25.923	2	08.542	4
45.371	2	(37.040)	3	27.393	8
46.905	3	40.514	3	69.524	2

γ AQUILAE.

λ	n	λ	n	λ	n
4219.387	2	4332.823	5	4404.871	3
36.012	3	34.042	8	12.277	9
39.885	2	39.609	6	15.211	6
45.388	2	44.520	3	25.817	9
46.886	2	52.903	6	27.359	8
50.798	2	59.721	2	30.280	3
58.454	4	69.905	2	66.675	3
74.901	3	71.314	9	72.827	5
94.218	3	79.339	3	82.340	3
4314.310	2	91.868	2	94.419	3
20.901	4	95.235	7	22.615	4

ε PEGASI.

λ	n	λ	n	λ	n
4200.151	2	4333.005	4	4415.408	3
19.582	6	34.172	6	23.096	3
20.487	2	37.285	1	25.939	8
36.106	3	44.650	2	27.536	7
45.434	1	53.043	6	30.490	4
47.073	1	71.425	8	66.826	7
58.561	3	76.214	1	72.977	4
74.994	1	83.739	1	94.640	4
88.236	1	4400.806	1	4522.888	5
4318.972	5	04.952	1	28.755	3
21.030	3	12.377	7	31.167	2

γ CEPHEI.

λ	n	λ	n	λ	n
4219.751	1	4314.574	3	4454.331	2
35.504	2	40.051	1	66.138	1
36.639	1	51.448	3	70.680	1
39.374	1	52.371	3	72.419	1
44.877	1	59.194	1	75.602	1
46.077	1	70.776	1	4522.285	1
50.371	1	4414.776	2	24.067	1
67.460	1	25.284	2	28.251	1
91.676	1	26.832	3	35.513	1
93.687	3				

PULKOWA,
January 1904.

THE SPECTRA OF MIXED GASES.

By P. G. NUTTING.

EARLY in spectroscopic work it was observed that mixed gases, electrically excited, frequently gave the spectrum of a heavy metallic component more strongly than that of a lighter component. In 1878 E. Wiedemann[1] described experiments with mercury and sodium in hydrogen and nitrogen. He proved that the intensities of the metallic spectra were out of all proportion to the relative amounts of metallic vapor present. It is a matter of common experience, in preparing Plücker tubes to exhibit metallic spectra, that as soon as the tube is heated sufficiently to vaporize the contained metal, the spectrum of the lighter gas filling the tube disappears. Recently Professor Percival Lewis has shown[2] that when mercury vapor is present in a tube of hydrogen, it will reduce the hydrogen spectrum to about half its original intensity when but one molecule of mercury to three thousand of hydrogen are present. It is well known that the cadmium spectrum will swamp that of hydrogen long before the cadmium is even melted. The red lines of the two spectra are equal at a temperature of about 200° C.

At first thought, we should say in explanation that the vapor of a metal would be a better electrical conductor than that of a non-metal and, carrying the most of the current, would show the brightest spectrum. But this hypothesis is clearly untenable. Although gas conductivities have not yet been accurately determined nor yet even defined, it is well known that, under the same conditions, metallic vapors do not differ widely from non-metallic vapors and the permanent gases in conducting power. And even then, why should the vast majority of lighter molecules be left idle as soon as a few of the heavier molecules are present?

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[1] *Wied. Ann.*, **5**, 500–524, 1878.

[2] ASTROPHYSICAL JOURNAL, **10**, 137–163, 1899; *Annalen der Physik*, **2**, 447–458, 1900.

Taking up the problem at this point, it was quickly shown that metallic character has little, if anything, to do with spectral predominance. Sulphur and iodine are nearly as effective in swamping hydrogen and nitrogen as are mercury or cadmium. Further, a non-metallic vapor may swamp a metallic. This was shown by a combination of sodium with bromine and iodine vapors. Iodine was found to be much more effective than chlorine, and this suggested that atomic weight might be the ruling factor. Even the persistent mercury spectrum may be displaced by the slightly heavier thallium, iodine easily swamps chlorine and sulphur, while any of the heavier metals displace sodium, itself so persistent in lighter gases. In all, about eighty combinations of the fifteen available vaporizable elements were tested without any contradictions to the atomic weight law being discovered; but several combinations, like cadmium and indium, oxygen and nitrogen, of elements of nearly equal atomic weight, would require a more accurate determination of relative pressure and spectral energy to be used in evidence. The law may be stated thus: In the spectrum of a mixture of gases, other things being equal, *the spectrum of the gas of greater atomic weight will be brighter.* This applies to such simple, moderate, fairly homogeneous excitation as we have in a Plücker tube containing gases under a pressure of from 0.1 mm to 10 mm, carrying a current of not more than 10 milliamperes. Outside these limits, the atomic weight effect is always less, *i. e.*, the intensities of the spectra are more nearly in proportion to the relative amounts of the gases present. In the luminous portions of the arc and spark, conditions of pressure, current density, etc., are so complex that a test is almost hopeless.

The greater part of the work here described was done with small Plücker tubes excited by a 2,000-volt alternating current. Sometimes a small induction coil was used. Tests of easily vaporizable substances were repeated with tubes having external electrodes. Other tests were repeated with small electrodeless tubes excited by electric waves from a Seibt quarter-wave resonance apparatus. It is hoped soon to carry the work much further by using this apparatus to excite tubes of quartz in which even silver and copper may be vaporized. Spectra were examined with a small direct-vision spectroscope; on account of the greater ease in identifying and comparing spectra, a low dispersion is preferable. Except in a few instances, the effects to be observed were so pronounced that no accurate photometry nor measurements of the relative amounts of gases present were necessary. Sometimes the two spectra were brought to equality and relative pressure estimated, and sometimes the tube was filled with nearly equal quantities of the two vapors and relative spectral energies estimated. A list of the tests made is given below. A parenthesis indicates that more accurate measurements are necessary to decide spectral predominance for equal proportions.

Atomic Weight	Element	*Tl*	*Hg*	*I*	*Te*	*In*	*Cd*	*Br*	*Se*	*Zn*	*Cl*	*S*	*Na*	*O*	*N*
1.......	*H*	+	+	+	+	+	+	+	+	+	+	+	+	?	+
14.......	*N*	+	+	+	+	+	+	+	+	+	(+)	+	+	(+)	
16.......	*O*	+	+				+				(+)	+	+		
23.......	*Na*		+	+	+	+	+	+	+	+	+				
32.......	*S*	+	+	+	+	+	+	+	+	+	(+)				
35.......	*Cl*	+	+	+			+	+							
65.......	*Zn*	+	+				+								
79.......	*Se*		+	+		+	+								
80.......	*Br*	+	+	+			+								
112.......	*Cd*	+	+	+	+	(+)									
114.......	*In*	+	+												
125.......	*Te*														
127.......	*I*	+	+												
200.......	*Hg*	(+)													
204.......	*Tl*														

In addition to these results may be cited the work of Collie and Ramsay[1] on mixtures of argon and helium. They found that a little argon mixed with helium showed the spectrum of the former strongly, while a small percentage of helium in argon showed but a faint helium spectrum.

Chemical combination occurs in the vast majority of cases, but compound spectra occur only in the case of a few halides. If we start with, say, hydrogen and sulphur, vaporize the sulphur while the discharge is passing, then allow the tube to cool, we get no spectrum other than those of hydrogen and sulphur during the process and no trace of H_2S on opening the tube. The result is the same when we fill the tube with H_2S at the start, and similarly with black mercury sulphide, except that a heavy deposit of sulphide remains. Even with the cadmium-oxygen combination, where the product cannot be kept vaporized, the two spectra may be observed superposed during combination. But with the mercury halides a strong band appears, brighter even than the mercury spectrum. The halogen spectrum remains visible as well as the mercury, evidently in proportion to the atomic weights of these substances, but the compound spectrum is brighter than either, possibly in proportion to the molecular weight of the compound. It would be in accord with theory if the spectra of compounds followed a molecular weight law, but observations yet made are far too meager to establish it. Varying the pressure over quite a range does not generally affect the preponderance of one spectrum over another. But at very high or very low pressure the spectrum of the lighter gas is stronger in proportion than at intermediate pressures. Changes in temperature have little effect so long as all components and products remain vaporized.

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[1] *Proc. R. S.*, **259**, 57-270, 1896.

Changes in current density over quite a wide range do not affect the spectral preponderance. But an excessive current density was found to increase the relative intensity of the lighter gas in every case observed. This test was made with some special Plücker tubes having a third bulb in the middle of the capillary. Though the central bulb had several hundred times the cross-section of the neighboring capillary, the spectra of the two portions never differed greatly. But a large tube with large bulbs and very fine capillary, filled originally with damp hydrogen, after considerable use showed a nearly pure hydrogen spectrum in the capillary, but a nearly pure oxygen spectrum (evidently from decomposed water vapor) in the bulbs. When the gas pressure in an ordinary Plücker tube is so great that a condenser in shunt alters the form of the discharge, say at 2 to 12mm, the effect of the capacity is invariably to intensify the spectrum of the lighter gas, *i. e.*, to oppose the effect of greater atomic weight. It is very difficult to exhaust a mercury tube so thoroughly, even if the mercury be kept boiling for a long time, that the air or hydrogen lines will not show with a condenser in parallel.

Frequently one spectrum will swamp the nearest lines of the second spectrum first. This effect is most marked in combinations of some metallic vapor with nitrogen or a halogen. Combinations with the sulphur group, however, show no trace of this effect. Thallium appears to weaken the *distant* (red) oxygen lines most.

No attempt at quantitative work has been made, nor any attempt to establish a quantitative relation between spectral preponderance and atomic or molecular weight. Judging by the work here, relative spectral energy might well be proportional to atomic weight; it certainly is not less, but may well be more than proportional.

In conclusion, it may be well to call attention to the simple explanation of the observed phenomena afforded by modern electron theory. Consider a current consisting of a convection of charged particles. Consider luminous and ultra-violet radiation as due to vibrations of the electrons within the atom. Excitation would be due to the impact of electrons, largely negative. The larger atoms would not only be hit most frequently, but would shield the smaller atoms from impact by the negative electrons. At very low pressures the shielding action would be less in proportion. Irregular heat motion would have little effect on either total or relative excitation. Increasing the current would increase the number of exciting electrons in proportion. The relative excitation (of large and small atoms) would remain unchanged, while the total excitation would be proportional to the current. While with moderate currents probably but a single electron is torn from an atom, excessive currents might still further break up the atom, and so produce a more and more continuous spectrum. In the rare instances of molecules so stable as to withstand having a fourth of their charge suddenly torn away, the electrons in the combined atoms would still be able to vibrate, but with altered and greatly damped vibrations. The large molecules would receive greater excitation than any atoms present. Hence compound spectra, when they do occur, are banded and relatively intense. Oscillating discharges would excite the smaller atoms relatively more than continuous currents.

If the exciting negative electrons are all alike, no matter from what atoms they are torn, one cannot properly speak of the current being carried by one gas of a mixture more than by another. Distribution of spectral energy would not then be a matter of distribution of current.

NATIONAL BUREAU OF STANDARDS,
Washington, December 1903.

ON DOUBLE REVERSAL.

By H. KONEN and A. HAGENBACH.

IN his interesting article on double reversal in the October number of this JOURNAL,[1] Humphreys finds that in general every double reversal is an apparent one and is occasioned by secondary influences, such as superposition of different orders, broadening, the simultaneous action of several sources of light, etc.

In view of the small number of observers whose results on this subject have been so far published, it will perhaps be of service if we describe some of the material that we find on our photographs, which leads us to almost the same conclusions that Humphreys reaches. The fact that our observations for the most part refer to the same lines as those of Humphreys has not led us to suppress this note, because the comparative infrequency of the phenomenon and its limitation to a rather small number of lines seem to indicate that just these lines are the only ones that can come into consideration in observations of multiple reversal.

We state in advance that, in agreement with Humphreys, and in contradiction to Liveing and Dewar,[2] we have never been able to observe double reversals visually in a simple arc.

We classify multiple reversals as apparent, real, and doubtful. Aside from the case of two arcs given by Humphreys, we observe five sorts, as follows: (1) superposition of two lines of different orders in grating spectra; (2) superposition of emissions which are not simultaneous; (3) action of different portions of the source of light; (4) superposition of lines of the same order; (5) unsymmetrical or symmetrical reversal combined with broadening.

We can cite, as examples of (1), among others, the magnesium line at λ 2852.25, in addition to those given by Humphreys. This coincides approximately in the second order with the *Mg* line at λ 5711.56. If the first is markedly widened, a bright line is seen unsymmetrically situated in the reversal. Fig. 1 of Plate XIV is a reproduction of a portion of such a reversed line, together with the line at λ 5711.56. It is, of course, self-evident that in every apparent self-reversal of the first kind the components can be resolved by a separation of the orders.

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[1] ASTROPHYSICAL JOURNAL, **18**, 204–210, 1903.

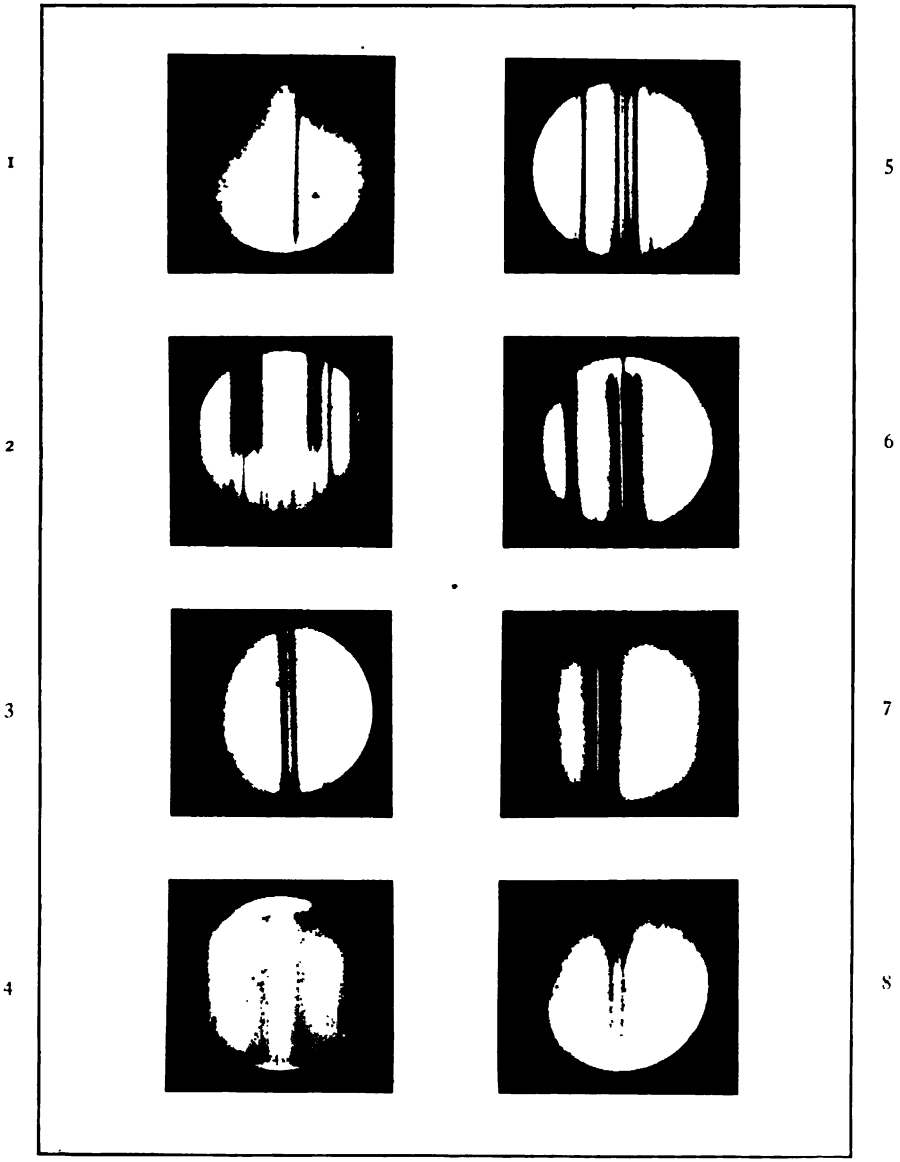
[2] *Proceedings of the Cambridge Philosophical Society*, **4**, 256–265, 1882.

Examples of (2) can be readily observed in the higher orders of grating spectra. Humphreys describes the appearance for the silver line at λ 3383.00. We cite among them the iron lines at λλ 3720.08, 3735.02, 3737.28. These lines were first photographed in the third order over the whole plate when there was but little iron in the arc; then the edges of the plate were covered and one of the carbons was replaced by an iron pole. The result is a series of apparent doubly reversed lines, the parts of which were, however, emitted at different times. It is illustrated in Fig. 2, where the first emission is seen below, and the superposition of the two above. A further illustration is given by the two D lines in Fig. 3, which was obtained with a small grating during an exposure of the red portion of the iron spectrum. No double reversal could be seen visually during the rather protracted exposure, but the appearance of the D lines doubtless constantly oscillated between relative sharpness and self-reversal.

The cases named under (3) and (4) we shall treat together, as they cannot be separated with certainty. The first surely cannot be excluded on *a priori* grounds, when we recall the actual differences in the spatial distribution of the emission of the arc, and when we consider that we either simultaneously illuminate each point of the slit with rays coming from different parts of the arc, or, in case an image of the source is projected upon the slit, we employ different parts of the arc on account of its motions. The astigmatism of the grating must also be taken into account. The possibility under discussion will particularly arise if other lines of the same element in the same order are also seen simultaneously in the reversal or double reversal. But then the *Auffassung* is different in each case.

Humphreys finds the iron line λ 3092.87 is a reversal of the aluminum line at λ 3092.84, and he explains this apparent double

PLATE XIV.



Double Reversal.

reversal on the assumption that the cooler aluminum vapor in the outer parts of the arc absorbs the light of the radiating nucleus, but not that of the iron vapor, since the emission of the two metals overpowers the absorption of the aluminum vapor.

We find a similar case with the magnesium line at λ 2852.25, in the broad reversed center (total width about 85 tenth-meters, of the reversal 17 tenth-meters) of which may be seen the two bright magnesium lines at λλ 2846.9 and 2848.5, in addition to a second reversal (of width about 2 tenth-meters). See Fig. 4, Plate XIV.

In this case the arc was projected upon the slit by a lens. But the effect of an action of the different parts of the arc does not seem to us excluded by that fact, although it must be admitted that this view is somewhat artificial. This is also true when we attempt to apply Humphreys' explanation to this case, as we must then assume that the absorptive power possessed by the magnesium vapor on account of its emission lines at λλ 2846.9 and 2848.5 is of a different order from that pertaining to the wave-length 2852; that is, we should have to designate the lines λλ 2846.9 and 2848.5 as "short" in the sense that term was used by Lockyer. Now, the last two belong to the series lines, while λ 2852 does not; but, in view of the circumstance first mentioned, we cannot regard such an assumption as permissible without further facts. The reasoning, which evidently can be easily expressed with the aid of Kirchhoff's law, can also be applied to the example given by Humphreys. We nevertheless prefer to leave open the question as to which of the two possibilities has the greater probability.

We name as examples of the fifth sort of apparent double reversal the lines λλ 3021.19, 3027.76, 2973.41, and 2973.17, already cited by Humphreys, but repeatedly observed by us before we had known of his paper. As to the last two lines, reproduced in Fig. 5, we have nothing to add to the description by Humphreys; but we find the details in case of the lines at λ 3021 a little different from his description. Fig. 6 pictures the three lines at λλ 3021.19, 3020.76, and 3020.62 with an average amount of vapor. The plate was taken in the third order, and, as a consequence, the line at λ 4531.33 in the second order falls between λλ 3020.76 and 3021.19, as may be seen at the lower part of the figure where the orders are separated. With greater quantities of vapor the line at λ 3020.76 broadens out particularly, and an apparent, unsymmetrical, double reversal results from the absorption of the common edge of the lines at λλ 3020.76 and 3020.62 (Fig. 7). A further example of this sort of double reversal is given by the cadmium lines at λλ 3467.76 and 3466.33.

We believe that we meet with a true double reversal in case of the magnesium line at λ 2852.25. If a large piece of magnesium is inserted in the arc, or if magnesium rods are employed as poles, the magnesium will begin to burn at a particular moment. If the arc is now extinguished and then quickly relit, a large amount of magnesium vapor develops explosively, and bursts out from the arc. A plate was taken with a small concave grating at just this moment, with a very short exposure, less than one-half second. This time was fully sufficient for obtaining a distinct and fully exposed plate, but an exposure of one-fourth second proved to be insufficient. All plates taken under these circumstances show the *Mg* line at λ 2852 as immensely broadened and multiply reversed.

None of the cases mentioned hitherto seems to be involved, for, in view of the briefness of the exposure, which represents the lower limit, the action of successive stages of emission may be presumed to be excluded. The regularity of the process further precludes the accidental effect of different parts of the arc. The conditions are evidently literally the same as those described by Liveing and Dewar,[1] and hence we do not doubt a true multiple reversal is obtained in this experiment.

The objection could be made that during the short exposure the arc was repeatedly lighted, so that we had the case studied by Humphreys. But absolutely nothing of the sort could be seen, if two separate circuits are required. If it should nevertheless be assumed that the two arcs might be fused into one, then our case does not in fact exclude that possibility. But in that event we see no difference from the old view, which assumes different strata of emission and temperature.

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[1] *Loc. cit.*

We find on our plates a number of other double reversals, but we cannot give the conditions necessary to their production, and we therefore would designate them as doubtful, Instances are the D lines; *Ag* 3383.00, 3280.80; *Al* 3961.68, 3944.16, (both together, Fig. 8).

Otherwise we agree with Humphreys that the majority of the double reversals observed on photographs are only apparent, but we think that genuine cases do occur and that this happened in the instance given by Liveing and Dewar.

UNIVERSITÄT BONN,
December 1903.

ON THE WAVE-LENGTH OF THE CADMIUM LINE AT λ5086.

By CHARLES FABRY.

IN their beautiful investigation on the absolute values of wave-length, Michelson and Benoit[1] measured the wave-lengths of several of the lines of cadmium. They obtained for the ratio of the wave-lengths of the red line at λ6438 and the green line at λ5086 the value 1.2659644.

On measuring the same ratio, Hamy[2] found the sensibly different value of 1.26594487. Regarding the wave-length of the red line as fixed,[3] that would correspond to a discrepancy of 0.0784 tenth-meter for the green ray, or relatively to an error of 15 millionths.

This decided divergence has attracted the attention of several spectroscopists,[4] and seems to have thrown some doubt either upon the accuracy of measurements by the interference method or upon the invariability of the standard of wave-length derived from the spectrum of cadmium. An attentive reading of M. Hamy's papers ought to show clearly enough the cause of the discrepancy: the green line measured by Hamy *is not the same* as that observed by Michelson and Benoit. Meanwhile, on account of the importance of this question to spectroscopy, I have thought I ought to undertake a detailed examination of the matter.

I must remind the reader that M. Hamy employed a tube of cadmium vapor *without electrodes*, fed by an induction coil with a condenser in parallel. M. Michelson used a tube with electrodes. Hamy's tube gave a more complex spectrum than did Michelson's, which yielded only the *arc lines*, or the other lines only very feebly, while Hamy's tube showed the *spark lines* besides.

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[1] *Travaux et Mémoires des Bureau International des poids et mesures*, Tome **11**.

[2] *Comptes Rendus*, **130**, 490, 1900.

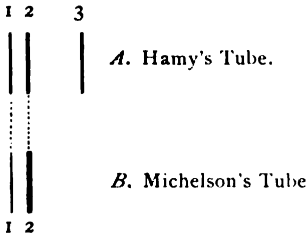
[3] M. Hamy has verified the perfect identity of the wave-length of the red line given by his tube with that given by Michelson's tube. *Comptes Rendus*, **130**, 700, 1900.

[4] LOUIS BELL, ASTROPHYSICAL JOURNAL, **15**, 157, 1902; *ibid.*, **18**, 191, 1903. J. HARTMANN, *ibid.*, **18**, 187, 1903.

I then examined the line at λ5086 produced by an Hamy tube by the powerful spectroscopic method devised by M. Perot and myself, which is based on the employment of fringes from silver films. I found that the line is a triplet, having the appearance shown in Fig. 1, *A*. This result is in perfect accord with that found by Hamy, as shown in the following paragraph from one of his notes:[1]

> The ray at λ508 emitted by my tubes without internal electrodes is triple. Under the conditions of my experiments, that radiation is composed of one simple line and a pair of equal intensity. My measures refer to the simple line, which is the least refrangible of the three composing the group.

It thus appears that the line measured by Hamy is certainly the one numbered 3 in Fig. 1. I found, moreover, that the relative intensities of the three components are very variable, but the study of that question would lead us beyond the subject in hand. I shall probably have occasion to return to it later.



Wave-lengths increase toward the right.
Scale about 10 cm to the tenth-meter.

FIG. 1.

The same radiation, on the other hand, given by Michelson's tube is a double, composed of two very unequal lines, as seen in *B*, Fig. 1. I have assured myself of the perfect coincidence of these two lines with 1 and 2 (Fig. 1, *A*) given by Hamy's tube. Line 2 is much the more brilliant in Michelson's tube. I have often found line 3 excessively faint. It is certain it was line 2 which was measured by Michelson and Benoit.

There would therefore have been good ground for surprise if the two series of measures had led to the same result.

I have measured directly the interval between lines 2 and 3, and find a difference of 0.076 tenth-meter, which establishes an agreement (at least to three ten-millionths) between the values of Hamy and of Michelson.

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[1] *Comptes Rendus*, 130, 700, 1900.

From the existence of these close and variable lines, it is certain that the line is not at all suitable for serving as a standard. I would remark here that no confusion is possible, if a little care is taken. The method of fringes from silver films permits the separation of the closest lines without any confusion whatever; if an unusual component should be developed, it would be seen at once. I should add that it has never happened in the course of several years of work during which M. Perot and I have constantly employed a Michelson tube. In that tube the principal component of the green line (2 in Fig. 1) is so predominant that the line may almost be regarded as simple.

Hence if it is desirable to preserve as the fundamental standard the red line, which is perfectly simple, there can be no inconvenience in the use of the green line as a secondary standard known with extreme precision.

The appearance and disappearance, according to circumstances, of the satellite lines still remains a most curious fact, the close study of which should lead to interesting results.

UNIVERSITÉ DE MARSEILLE,
December 1903.

ON THE CORRECTIONS TO ROWLAND'S WAVE-LENGTHS.

By C. FABRY and A. PEROT.

IN his recent article on "The Perot-Fabry corrections of Rowland's Wave-Lengths"[1] Louis Bell recalls, with reason, the fact that the wave-lengths in the solar spectrum may be altered by the radial velocity of the observer, due to the rotation of the Earth as well as to the eccentricity of its orbit. This cause of error was carefully examined during the preparation of our experiments, and we took care to choose our conditions so that it was negligible. But, inasmuch as we omitted to call special attention to this point in our memoir, it will not be superfluous for us to give a few points on the subject.

Although the preparation for our experiments consumed a year, the definitive measures were made between June 25 and July 6, 1901. The Earth having been at aphelion on July 4, the velocity[2] of the center of the Earth with respect to the Sun varied between +0.08km and −0.02km. The corresponding correction for wave-length 6000 changes from +0.0016 to −0.0004 tenth-meters. Furthermore, the observations were made between 10:30 A. M. and noon, and the radial velocity due to the diurnal motion varied between −0.12km and 0, to which corresponds a correction of from −0.0024 tenth-meter to 0.

The two corrections are separately negligible, and are almost always of opposite sign. The largest total correction does not attain a relative value of 4 ten-millionths. It should be further remarked that each line was measured several times on different days and at different hours, whence the errors, in any case so small, could not but be eliminated in the mean.

In an interesting article published in this JOURNAL,[3] Hartmann has remarked that our curve of corrections to Rowland's values was not applicable to the metallic lines. We ought to state expressly here that our curve, deduced solely from observations in the solar spectrum, does not apply to any wave-lengths of that spectrum except as they are given in Rowland's "Preliminary Table." As to the numerical values of Rowland, relative to the metallic lines, the fact is known that the results of the measures have undergone modifications[1] which without doubt render it difficult to adopt systematic corrections. Hartmann's discussion seems to confirm that view. It would no doubt be a useful piece of work to compare a certain number of metallic lines with those of the solar spectrum, the wave-lengths of which are now known at least to about one-millionth.

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[1] ASTROPHYSICAL JOURNAL, 18, 191, 1903.

[2] Computed by the formulæ given by FROST, ASTROPHYSICAL JOURNAL, 10, 283, 1899.

[3] "A Revision of Rowland's System of Wave-Lengths," 18, 167, 1903.

The corrections which we have found for the Rowland values have the effect, not only of causing the disappearance of the errors in the relative wave-lengths, but also of correcting them absolutely, so as to make them accord with the absolute values of the cadmium wave-lengths found by Michelson and Benoit. It is evident that if it was desired solely to correct the values relatively, without considering the absolute values, smaller corrections could be used than those we have given. This is what Hartmann proposes to do: the curve of corrections which he has calculated, a simple transformation of ours, is obtained on the basis of departing from a unit of length so chosen that the positive and negative corrections will be equally divided. That amounts to taking a new unit of length slightly different from that of the metric system. From the point of view of astrophysics alone, the choice of the unit of length is certainly a matter of indifference, but this is not the same for other applications. It would be annoying that one and the same wave-length should be represented by two numbers according to the application that is in view. Consequently it seems difficult to regard the solution proposed by M. Hartmann as other than provisional.

UNIVERSITÉ DE MARSEILLE,
CONSERVATOIRE DES ARTS ET MÉTIERS, PARIS,
December 1903.

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[1] On this point see HARTMANN, *loc. cit.*, p. 170; ROWLAND, *Memoirs of the American Academy*, **12**, 116, 189; JEWELL, ASTROPHYSICAL JOURNAL, **3**, 89, 1896.

PHOTOGRAPHIC OBSERVATIONS OF COMET 1903 *c* (BORRELLY).[1]

By SEBASTIAN ALBRECHT.

THIRTY-SIX negatives of Comet 1903 *c* (Borrelly) were secured between June 22 and August 18 inclusive, with the Crocker telescope, the Pierson camera, and the Floyd camera.[2] The original negatives were taken by Mr. R. H. Curtiss and myself, except on two nights when both were engaged in other work, and Mr. J. D. Maddrill kindly made these exposures for us. Table IV contains a list of the negatives. The smaller light-ratio of the Floyd telescope rendered the five plates taken with this instrument less suitable for measurement, and hence measures of these are not included in the tables.

Two distinct types of tails persist throughout the entire series of photographs. The principal tail is long and straight in its general direction, and in a large number of cases can be traced to the edge of the plate, a distance of 10°. It developed some very interesting forms, changing its aspect completely from day to day. Several more or less permanent features of the main tail deserve special mention. Its length was always considerable, and it was directed almost exactly away from the Sun. The deviation from the radius vector, which was negative before the middle of July, became positive after the Earth passed through the plane of the comet's orbit; in both cases, however, indicating a lag behind the radius vector. The main tail, in general, widens out after leaving the head, and on a large number of plates divides into two distinct branches. From measures of the angle between these two branches of the main tail on eight plates, the mean angular distance between them was found to be about 7°. There is a marked contrast in the appearance of the primary tail on the negatives taken in July and on those taken in August. The tail on the plates of July is, with three exceptions which will be mentioned later, smooth and continuous, while on the August plates it is twisted and full of condensations, indicating greatly increased activity as the comet approached perihelion. The accompanying illustrations show this feature very well.

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[1] Also to appear as a *Bulletin* of the Lick Observatory.

[2] For descriptions of these instruments see *L. O. Bulletin* No. 42, and *Pub. A. S. P.*, 7, 162, 1895.

The other tail is short and very much curved, and presents practically the same appearance on all the negatives. It is bright even on the plates of June. Its length is about 1°.5. On the plate of June 22 it made an angle of 26° with the primary tail. This angle gradually diminished, owing to the foreshortening produced by the Earth's approach to the plane of the comet's orbit, until about the middle of July, when the two tails appeared to coincide. After the passage of the Earth through the plane of the orbit, the angle again increased until August 18, when it amounted to 33°.

In addition to these two tails, occasional streamers developed, some of which branched off from the main tail, while others issued directly from the head. Some of these were of a more or less persistent nature, and in general they were narrow and straight. Their length varied somewhat, a part of the variation being probably due to unequal exposures. The following table illustrates the persistent nature of these streamers:

TABLE I.

Principal Streamers Issuing from the Comet's Head.

Plate	Date	Streamers Preceding t	Streamers Following t
11	July 16	....	5°.5
12	July 17	....	Not on plate
13	July 17	....	7.5
14	July 18	....	Not on plate
15	July 18	....	8.5
16	July 19	7°.0	7.5
17	July 19	7.5	
18	July 20	6.5	
19	July 20	6.0	
27	Aug. 11	5.0	11.0
28	Aug. 12	5.5	10.5
29	Aug. 13	6.5	Several streamers from tail
30	Aug. 14	7.5	9.0
31	Aug. 15	11.0[1]	7.0
32	Aug. 18	7.0 (faint)	8.5 (faint)

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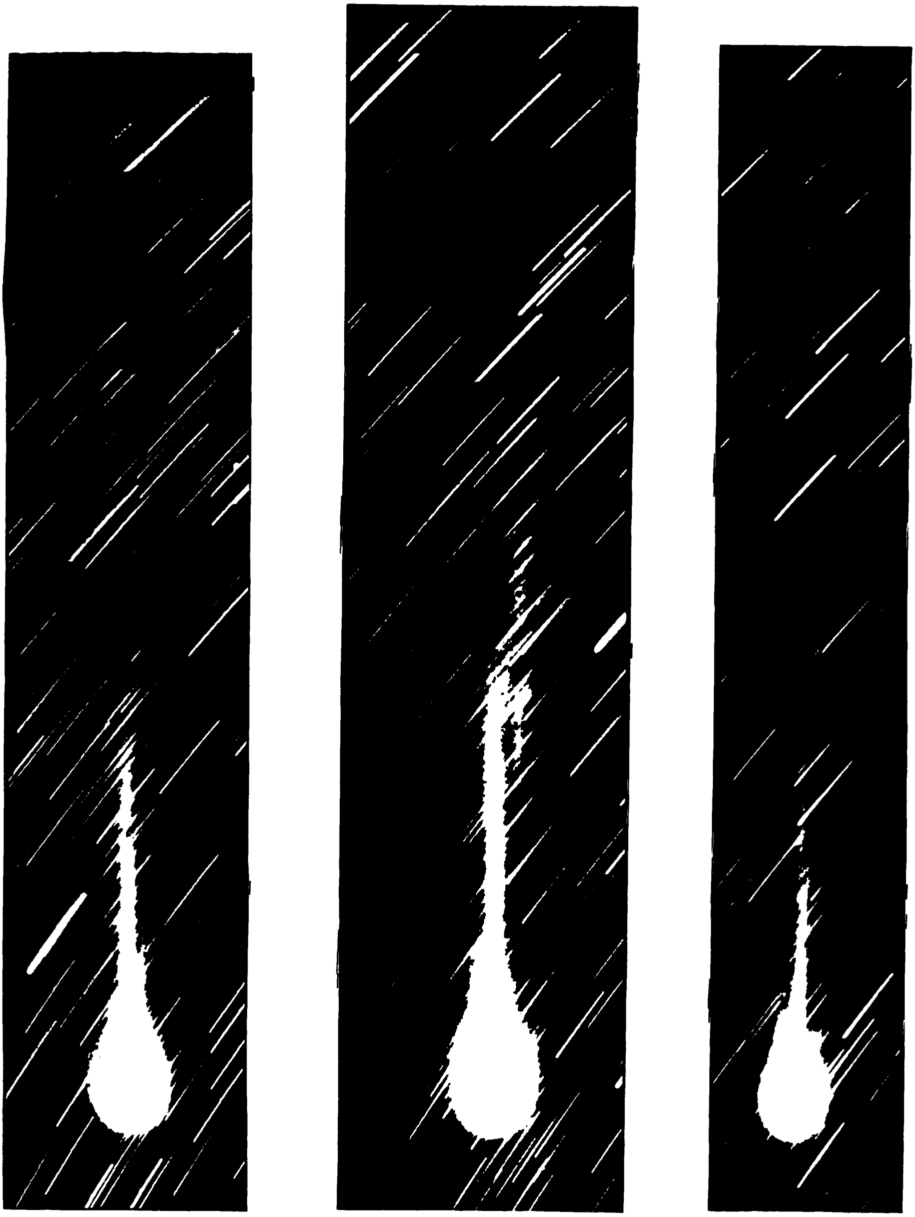
[1] One-fourth of a degree from the head this streamer has a sharp bend, and then makes an angle of 8° with t_1.

PLATE XV.



July 23, $9^h\ 0^m$ to $14^h\ 30^m$. July 24, $9^h\ 0^m$ to $14^h\ 30^m$. July 25, $9^h\ 0^m$ to $15^h\ 0^m$.

COMET 1903 *c* (BORRELLY).

Three of the negatives, those of July 23, 24, and 26, deserve special mention, on account of unusual structure in the principal tail. The plate of July 23 shows two long masses entirely separated from the main tail at about 3°.5 from the head, and on the side following the radius vector. One of these extends to the edge of the plate, a distance of about 10° from the head. The main tail extends to a distance of about 5° from the head, and a long, narrow streamer leaves it about 2° from the head. These four branches, together with two prominent bands in the main tail near the head, all making small angles with the general direction of the tail, present a wave-like appearance. The entire main tail somewhat resembles a rope, one end of which is unraveled and which has two of the loose strands severed.

The plate of July 23 shows, in addition, an entirely new tail issuing from the head in advance of the radius vector, preceding it by 6°, but being bent toward the radius vector shortly after leaving the coma. This tail assumes the forked characteristic which the main tail shows on a majority of the plates. Its angular width is 4°.6, and on the original negative it can easily be traced to a distance of 4° from the head. The plate of July 24 does not record this extra tail. The plate of the 24th shows a detached section, preceding the radius vector, which is composed ot two distinct portions, the shorter being nearer the head and pointing directly toward it. This plate also records a detached streamer on the following side of the main tail, and directly opposite the detached section referred to above. The interval from the 23d to the 24th of July was evidently one of unusual activity. The plate of July 25 shows no unusual forms. The plate of July 26 shows the main tail broken at a distance of about 3°.5 from the head. (This plate is difficult to reproduce.)

I have made measures of the plate of July 24, and of the reproductions of plates of the same date made by Barnard and Wallace at the Yerkes Observatory, and one by Quenisset at Nanterre. The measures were made on the end of the section nearest the head, and the times used were the beginnings of the exposures. This seems to be the most reasonable assumption regarding the time to be used for purposes of comparison of the different plates, as there is very little doubt that the extreme near end of this impression was made within a few minutes of the beginning of the exposures, and that during the exposures the section receded from this point. Although the beginning of the exposure does not correspond exactly to the first impression on the plate, the plates will be comparable (if we disregard the effect of the different light-ratios of the lenses with which the negatives were taken), no matter what the duration of the exposures may be. In the tables N stands for the Nanterre photograph, Y_1 and Y_2 for the first and second Yerkes photographs, and L for the Lick photograph.

TABLE II.

Plate	Beginning of Exposure, G. M. T.	Distance of Near End of Section from Head
N	$11^h\ 00^m$	1° 39′
Y_1	14 57	2 19
L	17 00	2 50
Y_2	17 59	3 2

TABLE III.

Plates	Time Interval	Hourly Rate	Velocity of Recession	
			Miles per Second Relative to Head	Miles per Second Relative to Sun
N and Y_1	$3^h\ 57^m$	10′.1	28	6
N and L	6 00	11.8	33	11
N and Y_2	6 59	11.9	33	11
Y_1 and L	2 3	15.1	42	20
Y_1 and Y_2	3 2	14.2	39	17
L and Y_2	0 59	12.2	34	12

The discordances in the above rates of recession are probably partly due to unavoidable uncertainties of measures on such objects, and partly to the different light-ratios of the lenses with which the negatives were secured. They differ somewhat from those obtained by Barnard, but this must be expected on account of the different supposition in regard to the times to be used in the comparison of the negatives.

The short portion of the section, as shown on the Lick plate, represents, without much doubt, a trail made by a detached mass of cometary matter during the exposure. It is of interest to know the probable dimensions of the mass that produced this trail. Evidently the beginning of the trail was made by the end of the mass which was nearest the head, and the other end of the trail was made by the farther end of the mass. The duration of the exposure was $5^h\ 30^m$. If we use the average hourly rate of recession obtained above, 12′.6, the recession in five and one-half hours would be 69′. The measured length of mass and trail was 104′. Therefore the difference, 35′, represents the length of the mass that made the trail. Measures of the width of the trail give 16′ as the probable width of this mass.

Additional data with regard to the plates are contained in Tables IV and V. The comet's right ascensions and declinations were obtained by interpolation from Perrine's ephemeris (*L. O. Bulletin* No. 47), and from the early observations by Aitken and Maddrill, published in *Lick Observatory Bulletin* No. 49. For July 1 and 16, they were computed from the elements given in *Lick Observatory Bulletin* No. 47. The tables were computed by Bessel's formulæ as revised by Kreutz.[1] The designation of all the symbols used in the tables will be repeated here for purposes of ready reference.

t_1 and t_2 refer to the primary and secondary tails, respectively. p is the position angle, at the comet, of the pole of the comet's orbit. p' is the position angle of the Earth, at the pole of the comet's orbit, as seen from the comet. S is the angle at the comet between the pole of its orbital plane and the Earth. p_r is the position angle of the radius vector from the comet to the Sun. p_{t_1} and p_{t_2} are the position angles of the primary and secondary tails respectively. u_r is the angle between two planes through the comet, one of them containing the pole of the comet's orbit, and the north pole of the Earth; and the other containing the pole of its orbit and the radius vector from the Sun to the comet. u_{t_1} and u_{t_2} are similar angles, but in these cases the second plane contains the primary and secondary tails respec-

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[1] *Publikationen der Sternwarte in Kiel*, "Untersuchungen über das Cometen-System 1843 I, 1880 I und 1882 II," Part I, p. 85.

TABLE IV.

Plate No.	Date, 1903	Pacific Standard Time			Comet's α	Comet's δ	Remarks	Ob-server
		Begin-ning	End	Mid-Ex-posure				
1	June 22	13^h50^m	15^h35^m	14^h42^m	$21^h51^m.6$	− 6 59	t_1 very faint and short.	C.
2	June 23	11 45	15 30	13 37	21 50 . 8	− 6 5	t_1 narrow near head, then broadens.	C.
3	June 26	11 30	15 30	13 30	21 47 . 5	− 2 57	t_1 straight and very faint.	A.
4	June 29	12 20	13 13	12 46	21 42 . 8	+ 1 2	t_1 double, angle between branches 8°.	A.
5	June 30	11 33	15 33	13 33	21 40 . 7	+ 2 41	t_1 long, form indistinct, division in t_1.	C.
6	July 1	12 18	15 18	13 48	21 38 . 4	+ 4 27	t_1 sharp, narrow, single, and slightly curved.	A.
7	July 12	8 33	9 11	8 52	20 34 . 0	+39 32	t_1 4° long, somewhat indistinct.	A.
8	July 13	8 42	9 43	9 12	20 18 . 8	+44 36	t_1 straight and narrow.	A.
9	July 14	8 35	10 23	9 29	20 0 . 1	+49 42	t_1 long, narrow, straight, widening gradually.	A.
10	July 15	8 31	10 47	9 39	19 36 . 5	+54 39	t_1 long, straight, double (angle 7.5°).	A.
11	July 16	8 30	11 15	9 52	19 6 . 5	+59 11	t_1 straight and narrow, double near end.	A.
12	July 17	8 40	11 10	9 55	18 29 . 5	+63 10	t_1 long, straight, double (angle 8°).	C.
13	July 17	11 37	12 12	11 54	18 25 . 8	+63 25	t_1 double and straight, also streamer from t_1.	C.
14	July 18	8 40	10 35	9 38	17 44 . 7	+66 5	See footnotes to Table IV.	C.
15	July 18	11 00	12 00	11 30	17 40 . 6	+66 17	Coma bright; also 2 streamers from t_1.	C.
16	July 19	8 52	10 7	9 30	16 52 . 4	+67 59	t_1 very bright near head; streamer on each side of t_1.	A.
17	July 19	10 35	12 35	11 35	16 47 . 6	+68 6	Bright coma; t_1 straight; streamer 2° long.	A.
18	July 20	8 58	12 58	10 58	15 55 . 7	+68 45	t_1 fan-shaped; narrow streamer 4° long.	A.
19	July 20	14 10	15 10	14 40	15 47 . 8	+68 46	Strong coma; t_1 faint and somewhat indistinct.	A.
20	July 23	9 00	14 30	11 45	13 47 . 0	+65 38	See text.	C.
21	July 24	9 00	14 30	11 45	13 19 . 3	+63 53	See text.	C.
22	July 25	9 00	15 00	12 00	12 57 . 4	+62 0	t_1 double, streamer each side of it.	C.
23	July 26	9 03	14 33	11 48	12 39 . 9	+60 10	See text; taken through clouds.	A.
24	July 27	9 22	11 17	10 20	12 26 . 6	+58 30	See footnotes to Table IV.	M.
25	July 28	10 18	13 18	11 48	12 14 . 0	+56 42	Streamers; t_1 faint in places.	A.
26	July 29	11 08	12 38	11 53	12 4 . 1	+55 6	t_1 has bend 2½° from head; streamers on each side.	A.
27	Aug. 11	8 39	9 00	8 49	11 0 . 2	+40 56	t_1 curved; streamers from head and t_1.	A.
28	Aug. 12	8 30	9 30	9 00	10 56 . 9	+40 4	Streamers from t_1 and from head; t_1 curved.	A.
29	Aug. 13	8 35	9 50	9 12	10 53 . 7	+39 13	Streamers from t_1 and from head.	C.
30	Aug. 14	8 29	9 41	9 05	10 50 . 6	+38 23	Streamers from t_1 and from head.	M.
31	Aug. 15	8 25	9 25	8 55	10 47 . 6	+37 32	Streamers from t_1 and from head t_1 somewhat curved.	A.
32	Aug. 18	8 19	8 53	8 36	10 38 . 4	+34 53	Impression faint; streamers on each side of head.	A.

Plate 14.—t_1 double for 1½° from head; then single and straight, becoming quite narrow at 3° from head, and then again widening out somewhat. Also very faint at 1½° from head.

Plate 24.—t_1 very narrow near head. Becomes double shortly after leaving the head, with an angle of 7° between the branches. Also a very faint streamer on the side opposite the short tail. The long tail has bend shortly after leaving the head to which is due the large residual $p_{t_1} - p_r$ for this plate.

TABLE V.

Plate No.	Date, 1903	P. S. T.	P	P'	S	p_r	p_{t_1}	$p_{t_1}-p_r$	u_r
1	June 22	14^h42^m	260°.0	281°.4	56°.8	246°.0	248°.5	+2°.5	+109°.2
2	June 23	13 37	260.6	280.3	56.8	245.8	242.9	−2.9	+108.4
3	June 26	13 30	262.7	276.4	57.2	243.1	247.0	+3.9	+107.4
4	June 29	12 46	265.4	271.6	58.0	239.2	235.2	−4.0	+106.2
5	June 30	13 33	266.4	269.6	58.4	237.4	235.6	−1.8	+105.8
6	July 1	13 48	267.4	267.5	58.8	235.5	229.0	−6.5	+105.4
7	July 12	8 52	276.1	230.3	75.7	197.9	196.4	−1.5	+101.7
8	July 13	9 12	274.6	225.4	79.0	192.5	191.3	−1.2	+ 99.3
9	July 14	9 29	272.0	220.4	82.4	186.6	184.2	−2.4	+ 98.8
10	July 15	9 39	267.8	215.4	86.0	179.8	181.0	+1.2	+ 98.4
11	July 16	9 52	261.7	210.6	89.7	171.8	173.3	+1.5	+ 98.0
12	July 17	9 55	253.4	205.7	93.2	162.3	161.4	−0.9	+ 96.9
13	July 17	11 54	252.6	205.4	93.6	161.4	158.8	−2.6	+ 96.9
14	July 18	9 38	242.9	201.2	96.6	151.1	154.1	+3.0	+ 96.1
15	July 18	11 30	241.9	200.9	96.9	150.1	152.5	+2.4	+ 96.0
16	July 19	9 30	230.2	196.8	99.8	138.3	141.2	+2.9	+ 95.4
17	July 19	11 35	229.1	196.4	100.1	137.1	138.8	+1.7	+ 95.6
18	July 20	10 58	216.2	192.4	102.8	124.4	124.5	+0.1	+ 94.4
19	July 20	14 40	214.2	191.8	103.2	122.5	122.4	−0.1	+ 94.3
20	July 23	11 45	183.3	181.4	109.8	93.5	94.0	+0.5	+ 92.0
21	July 24	11 45	175.9	178.2	111.6	87.0	88.4	+1.4	+ 91.1
22	July 25	12 00	169.9	175.3	113.1	81.8	83.2	+1.4	+ 90.1
23	July 26	11 48	165.0	172.6	114.4	77.7	78.0	+0.3	+ 89.2
24	July 27	10 20	161.2	170.2	115.6	74.6	80.3	+5.7	+ 88.2
25	July 28	11 48	157.4	167.8	116.6	71.6	73.5	+1.9	+ 87.0
26	July 29	11 53	154.4	165.6	117.5	69.2	72.0	+2.8	+ 85.9
27	Aug. 11	8 49	132.5	146.0	122.5	46.6	46.9	+0.3	+ 63.6
28	Aug. 12	9 00	131.3	144.8	122.6	44.6	45.2	+0.6	+ 60.8
29	Aug. 13	9 12	130.1	143.5	122.7	42.5	43.6	+1.1	+ 58.0
30	Aug. 14	9 05	129.0	142.3	122.8	40.3	41.5	+1.2	+ 54.8
31	Aug. 15	8 55	127.8	141.1	122.8	38.1	39.7	+1.6	+ 51.6
32	Aug. 18	8 36	124.4	137.2	122.9	30.2	30.9	+0.7	+ 39.5

	Date, 1903	n	u_{t_1}	$u_{t_1}-u_r$	n_1	p_{t_2}	u_{t_2}	$u_{t_2}-u_r$	n_2
1	June 22	0°.559	107°.7	− 1°.4	0.56	222°.1	124°.4	+15	0.64
2	June 23	0.560	110.2	+ 1.7	0.57	222.5	123.5	+15	0.64
3	June 26	0.565	105.1	− 2.3	0.56	225.3	118.9	+12	0.63
4	June 29	0.571	108.7	+ 2.6	0.59	216.8	122.6	+16	0.69
5	June 30	0.575	107.0	+ 1.2	0.54	215.6	122.3	+17	0.70
6	July 1	0.580	109.8	+ 4.5	0.61	213.4	123.0	+18	0.72
7	July 12	0.797	103.8	+ 2.2	0.82	190.7	122.1	+20	0.95
8	July 13	0.816	103.8	+ 4.4	0.86	187.9	118.5	+19	0.96
9	July 14	0.856	.....	......	....	....	.....	....	....
10	July 15	0.891	.....	......	....	.....	.....	....	....
11	July 16	0.923	.....	......	....	.....	.....	....	....
12	July 17	0.947	.....	......	....	.....	.....	....	....
13	July 17	0.949	.....	......	....	.....	.....	....	....
14	July 18	0.966	.....	......	....	.....	.....	....	....
15	July 18	0.967	....	......	....	.....	.....	....	....
16	July 19	0.981	.....	......	....	.....	.....	....	....
17	July 19	0.983	.....	......	....	.....	.....	....	....
18	July 20	0.991	94.8	+ 0.4	0.99	.....	.....	....	....
19	July 20	0.992	93.9	− 0.4	0.99	.....	.....	....	....
20	July 23	1.000	93.5	+ 1.4	1.00	99.1	108.1	+16	0.96
21	July 24	0.999	95.0	+ 3.9	0.99	93.9	109.1	+18	0.94
22	July 25	0.997	93.6	+ 3.5	0.99	91.2	112.2	+22	0.91
23	July 26	0.994	89.8	+ 0.6	0.99	89.1	113.8	+25	0.88
24	July 27	0.992	100.7	+12.5	0.95	86.9	113.4	+25	0.87
25	July 28	0.990	91.2	+ 4.1	0.98	83.7	110.9	+24	0.87
26	July 29	0.987	91.8	+ 5.9	0.97	83.0	111.7	+26	0.85
27	Aug. 11	0.994	64.2	+ 0.6	0.99	68.7	98.5	+35	0.82
28	Aug. 12	0.996	62.0	+ 1.2	0.99	67.3	96.9	+36	0.82
29	Aug. 13	0.998	60.0	+ 2.0	1.00	71.1	101.6	+44	0.78
30	Aug. 14	0.999	57.0	+ 2.2	1.00	67.9	97.9	+43	0.80
31	Aug. 15	1.000	54.5	+ 3.0	1.00	64.7	94.2	+43	0.82
32	Aug. 18	0.994	53.6	+14.1	1.00	64.2	93.8	+54	0.79

tively. The quantities n, n_1 and n_2 express the foreshortening of the radius vector and two tails respectively, due to their inclination to the line of sight. As u_{t_1} and u_{t_2} become indeterminate at the time of the Earth's passage through the plane of the comet's orbit, these quantities were omitted, in Table IV, from July 14 to July 20.

The difference $u_{t_2}-u_r$ is the angle which the secondary tail makes with the radius vector. It will be seen that this angle increases continually from the time of first observation up to the time of last observation on August 18. This increase may be due to the fact that the speed of the nucleus in the orbit was rapidly accelerated up to the date of perihelion passage, August 27, thereby causing this tail to lag behind more and more.

The negatives selected for reproduction illustrate in a general way the rapid changes which the comet's tail underwent. The first ten of these negatives were taken with the Pierson camera, and the remaining two with the Crocker telescope. The scale of the original negatives has been preserved in all of the accompanying cuts.[1]

Acknowledgments are due to Assistant Astronomer Perrine and to Fellow R. H. Curtiss, for valuable suggestions made during the progress of the work, and to Fellow J. D. Maddrill for checking most of the computations.

LICK OBSERVATORY,
January 12, 1904.

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[1] Only three of these are reproduced in Plate XV.—EDS.

A PHENOMENON INVOLVED IN THE NEBULOSITY AROUND *NOVA PERSEI.*

By OTTO LUYTIES.

THE phenomenon described in this article is essentially a distortion phenomenon, affecting all sensible secondary radiations induced by new or varying primary emanations. The scope of the phenomenon, therefore, embraces a wide range of effect on terrestrial observations. As, however, its effect is most marked when the velocity of the primary emanations is greatest, it is particularly great in the case of astral emanations of high velocity. The discussion of this phase of its action is the purpose of this article.

While considering the nebulosity around *Nova Persei* two peculiarities attracted my attention: (1) the extreme rapidity of the expansion, and (2) its progressive retardation.

The expansion of the illumination was so rapid that on March 29, 1901, thirty-six days after the outburst of the *Nova*, Perrine observed the maximum radius of the inner and outer nebulous rings to be 89″ and 149″, and of an arc on the northeast side to be 321″.[1]

Assuming that the nebulous material moved, at least during the first part of its course, with a speed of 300,000 km a second, and applying this assumption to individual forms in turn, on the supposition that the initial motion was nearly radial, F. W. Very computes[2] from these radii $\pi = 0''.014$, $\pi = 0''.024$, $\pi = 0''.052$, respectively. From this and another computation in the same article he concludes that the parallax $0''.05$ may be definitely adopted as that of the *Nova*, and inferentially as that of the Milky Way in its vicinity. The objection to this computation is that it gives much smaller values for the dimensions of the Galaxy than appear probable from other considerations.

Now if, on the other hand, we assume the parallax of the

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[1] ASTROPHYSICAL JOURNAL, **16**, 252, 1902.

[2] *American Journal of Science*, **16**, 127, 1903.

Nova to be less, say only $0\rlap{.}''01$, as given by Chase and Aitken, and compute the velocity of the radiations from this, making the other assumptions the same as before, we obtain 1,500,000 km per second as the velocity of the emanations. This result appears highly improbable, as we have no knowledge of any velocity greater than that of light.

Concerning the determination of parallax and of the velocity of the radiations from *Nova Persei*, Seeliger concludes[1] that "nothing is known as to V if the parallax π of the *Nova* is unknown." On the following page he remarks:

> For every assumed value of π we can find the corresponding surface which represents the illuminated stratum of nebula. The parallax of the *Nova* therefore remains undetermined, and it is not determinable from measurements of the photographs which are before us without the aid of further and quite arbitrary hypotheses.

The second marked peculiarity of the nebulosity around *Nova Persei* is the progressive retardation of its expansion. This has been urged by Very as an objection to some of the hypotheses assigning the nebular phenomenon to the action of radiation from the *Nova* on diffused quiescent matter already existing in surrounding spaces. The phenomenon described herein, however, explains this retardation.

The computation of parallax mentioned above is open to the fatal objection that it involves two tacit assumptions, of which one is erroneous. Of these two assumptions, the correct one is that the outermost rays that reach our eye determine the outer limits of the apparent illumination. The other assumption, which is incorrect, is that these outermost rays are caused by emanations of some kind originally at right angles to our line of sight.

It should be observed that coincident with the appearance of a new star we see first those luminous rays which come from the nearest points of the nebula. As time passes, more distant portions of the nebula become visible. If the near surface of the nebula is convex, the area of this visible portion will increase rapidly, yet at a progressively retarded rate. If a spherical nebula should spring into existence at its full ultimate size, its apparent size would increase just as the portion of a sphere cut off by successive parallel planes increases. When, however, the nebula is produced by a central agency, the case is somewhat more complicated.

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[1] ASTROPHYSICAL JOURNAL, **16**, 189, November 1902.

Let us, in all the following, assume the Earth to be at such a great distance from the *Nova* that all rays from the nebulosity to the observer may be treated as parallel, without essential error.

Let us assume emanations radial and equal in all directions to cause the space surrounding a body to become luminous. Then the visible illuminated space will be part of a prolate ellipsoid of which the body is a focus. The distances from the focus to the apsides will be the product of the time and the velocities of the primary and secondary radiations divided by their sum and difference, respectively. From these functions all other dimensions of the ellipsoid can readily be computed. The apparent radius of the illumination will be equal to the conjugate radius of this ellipsoid. The distortion of the image of the nebulosity will be equal to the ratio of this radius to the semi-latus-rectum. This is true unless the maximum radius of the illumination is less than the transverse radius of the ellipse, in which case this radius (*OA* in Fig. 1) determines the limits of the illumination. (If, in a special case, the velocities are equal, the locus of farthest visible points in the nebulosity at any time will be, as suggested by Kapteyn, part of the surface of the ellipsoid whose foci are the radiating body and the Earth.) Then the complete locus of all sensible secondary points of radiation will be the portion of this ellipsoid which is included within a spiraloid of revolution whose radius is the greatest distance at which the primary emanations at successive periods can cause the secondary.

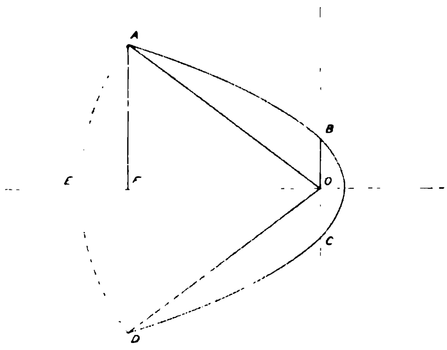

FIG. 1.

If, as a special case, we assume the primary emanations to travel with the speed of light, and to be of a uniformly sustained intensity in all directions, the form of the nebula will be a paraboloid with spherical base, as shown in section in Fig. 1. *OA* is equal to the maximum radius of the illumination (*i. e.*, the point *A* is as far as the illuminating action of the *Nova* can reach); *OE* and *OD* are equal to *OA*. The distance *OB* is the distance traveled by light during the visibility of the *Nova*, while the distance *FA* is the radius of the apparent illumination. *FA* increases at a very rapid rate, which is, however, progressively retarded from infinity to zero, and ultimately coincides with *OB*. I shall call (1) the ratio of this maximum radius (or the transverse radius of the ellipse, whichever is the smaller) to the distance traversed by the primary emanations in the time considered (*OA* to *OB* in the figure) the "extension;" (2) the ratio of the apparent radius to the distance covered by the primary emanations in the time considered (*FA* to *OB* in the figure) the "actual distortion;" and (3) the ratio of the apparent illumination to the distance covered by light in the time considered (*FA* to *EF* in the figure) the "relative distortion." I submit a table of these ratios for primary radiations with velocities of 1½ *V*, *V*, ¾ *V*, ½ *V*, and ¼ *V*, all for a maximum radius of ten units of time, where *V* is the velocity of the secondary radiations.

TABLE I.

Approximate Distortion of the Image.

"Extension"		Actual Distortion, *FA* to *OB*					Relative Distortion, *FA* to *EF*				
Time	$\frac{OA}{OB}$	1½ *V*	*V*	¾ *V*	½ *V*	¼ *V*	1½ *V*	*V*	¾ *V*	½ *V*	¼ *V*
1	10.00	5.49	4.36	1.51	1.15	1.03	8.24	4.36	1.13	0.58	0.26
2	5.00	2.95	3.00	1.51	1.15	1.03	4.42	3.00	1.13	0.58	0.26
3	3.33	2.00	2.38	1.51	1.15	1.03	3.13	2.38	1.13	0.58	0.26
4	2.50	1.61	2.00	1.51	1.15	1.03	2.42	2.00	1.13	0.58	0.26
5	2.00	1.32	1.73	1.51	1.15	1.03	1.98	1.73	1.13	0.58	0.26
6	1.67	1.11	1.53	1.50	1.15	1.03	1.67	1.53	1.12	0.58	0.26
7	1.43	0.95	1.36	1.47	1.15	1.03	1.43	1.36	1.09	0.58	0.26
8	1.25	0.83	1.22	1.39	1.15	1.03	1.24	1.22	1.04	0.58	0.26
9	1.11	0.72	1.10	1.32	1.15	1.03	1.08	1.10	0.99	0.58	0.26
10	1.00	0.63	1.00	1.25	1.15	1.03	0.94	1.00	0.94	0.58	0.26

Individual points in Fig. 1 might conceivably decrease in brightness approximately as the square of their distance from *O*. It should be observed, however, that the *Novæ* generally fade very rapidly, so that in an actual case only the paraboloidal shell *ABCD* will be very bright, and *OE* will be much shorter than *OA*. The radius *OA* is dependent on the radiating power of the *Nova;* if, therefore, the *Nova* does not radiate uniformly in all directions, *OA* will vary as it approaches *OB*. As *OA* is probably dependent on quiescent matter in the space about the *Nova*, it will vary with the distribution and susceptibility of this matter.

Let us consider a special case, with the following assumptions: (1) the nebulous matter to be uniform in distribution and susceptibility; (2) the primary emanations to be equal in all directions; (3) the primary emanations to travel with the same velocity as the secondary; (4) the maximum radius of the illumination to be ten units; (5) the primary emanations to decrease in intensity and radius of action as given in Table II. Then Figs. 2, 3, and 4 will be sections of the visible nebulosity at the time indicated for each.

TABLE II.

Radii of Illumination Assumed in Figs. 2, 3, 4.

FIRST ASSUMPTION			SECOND ASSUMPTION		
Time	Mag.	Rad. of Illum.	Time	Mag.	Rad. of Illum.
0	0	39.8	0	0	39.8
1/30	1	25.1	1	1	25.1
4/30	2	15.8	2	2	15.8
10/30	3	10.0	3	3	10.0
1	4	6.31	4	4	6.31
2	5	3.98	5	5	3.98
4	6	2.51	6	6	2.51
7	7	1.58	7	7	1.58
10	8	1.00	8	8	1.00
			9	9	0.60
			10	10	0.40

In order to consider a particular case, let us refer to the velocity of light as *V*, the parallax of the *Nova* as π, and the velocity of the unknown emanations from the *Nova* as V_1. Let us, for example, consider the photograph of *Nova Persei* taken

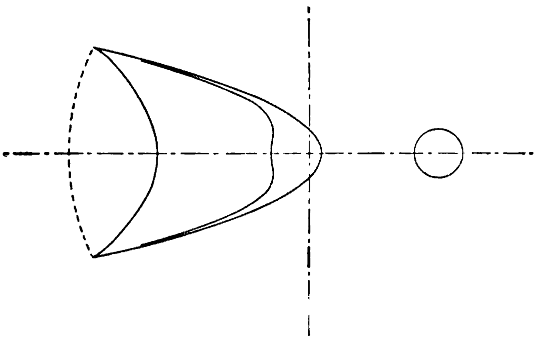

FIG. 2.

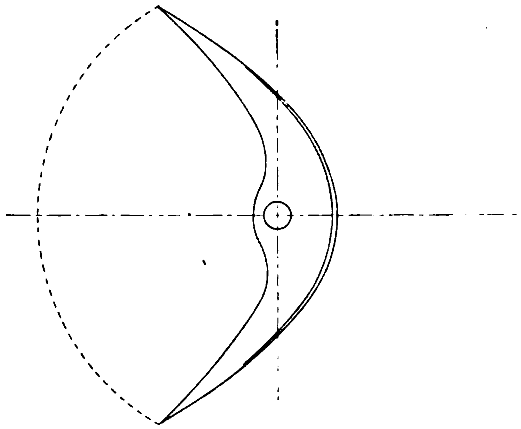

FIG. 3.

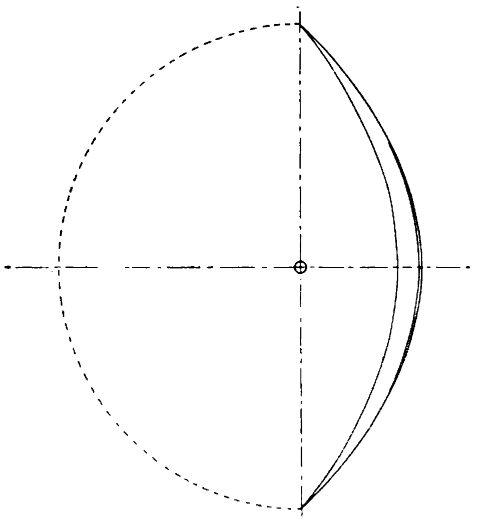

FIG. 4.

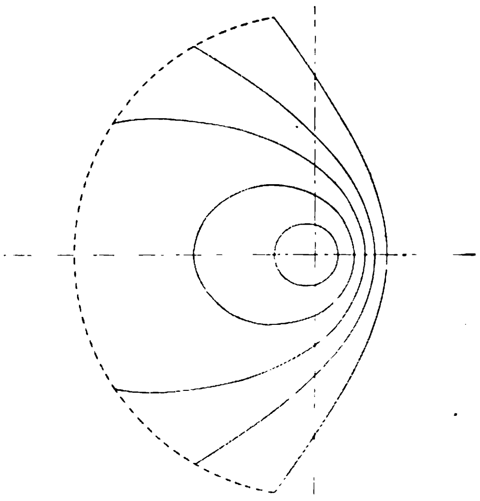

FIG. 5.

FIG. 2 shows in section the locus of visible points in the assumed nebula, after one unit of time. The small sketch to the right shows the relative size of a sphere expanding with the velocity of light during the same period.

FIG. 3 shows same after five units.

FIG. 4 shows same after ten units.

FIG. 5 shows the loci of all visible emanations traveling with velocities 1½ *V*, *V*, ¾ *V*, ½ *V*, and ¼ *V*. The parabola is the same as that given in Fig. 3.

by Perrine on March 29, 1901, showing nebulous material at a distance of 321″, 149″, and 89″ from the *Nova*. Let us suppose, for argument's sake, that emanations of various speeds are possible, with velocities of $1\frac{1}{2}\ V$, V, $\frac{1}{2}\ V$, and $\frac{1}{4}\ V$. Then, by the direct method, we obtain as follows from the outermost arc:

Assumed V_1	Direct π	Distortion	Corrected π
$V_1=1\frac{1}{2}\ V$	0″.035	8.24*	0″.004
$V_1=V$	0.052	4.36*	0.012
$V_1=\frac{1}{2}V$	0.104	1.15	0.090
$V_1=\frac{1}{4}V$	0.204	1.03	0.198

The distortions marked * for $V_1=1\frac{1}{2}\ V$ and $V_1=V$ are for an "extension" of 10, which is merely an estimate.

Now, as it is not probable, from other considerations, that the parallax of the *Nova* is as large as 0″.09 or as small as 0″.004, we can reasonably conclude that the velocity was V, nearly or exactly.

As a matter of fact, assumptions of velocities differing from that of light for the nebulosity about *Nova Persei* can be proved improbable from other considerations of this distortion phenomenon. Very has suggested[1] that

> Perrine's observation of March 29, 1901, indicates the existence, at that date, of two nebulous rings, with radii in the ratio of 1 : 2 and an arc on the N. E. side, which perhaps is the sole record of a third and wider ring. The three radii having approximately the ratio of 1 : 2 : 4 may correspond to ions having masses in the ratio of 4 : 2 : 1, and, if so, bear witness to the existence of at least three sorts of ions out of which, in varying proportions, we may conceive the atoms to be made.

If we observe, however, that the distortion corrections for this photograph are very different for V, $\frac{1}{2}\ V$, and $\frac{1}{4}\ V$, the apparent agreement for the outer arc is destroyed and the ratio of the inner to the outer ring is rendered less exact.

It will be evident from Table I that when the primary emanations have a smaller velocity than the secondary, the distortion is a constant. As, therefore, a nebula expanding with a velocity less than that of light would increase at a slow and uniform rate, we can safely conclude that the velocity of the emanations from *Nova Persei* was *not less* than that of light.

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[1] *Am. Jour. Sci.*, 16, 56.

Now if, on the other hand, the nebula, as variously suggested, had actually expanded with a velocity greatly in excess of that of light, then the nebulosity would have been visible *before the Nova*. Fig. 6 shows in section the loci, at the moment when the *Nova* itself becomes visible, of possible visible points in three nebulæ, expanding with velocities equal to 10 V, 2 V, and 1½ V.

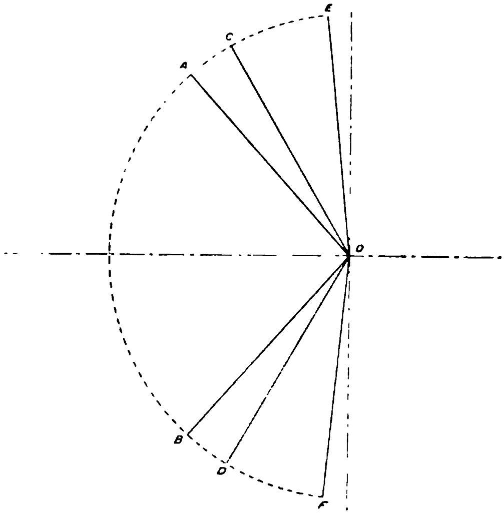

FIG. 6.

From the above discussion it appears evident that the emanations from *Nova Persei* must have traveled with approximately or exactly the velocity of light. It should be observed that this conclusion is entirely independent of all hypotheses as to the nature of these emanations.

I hope that someone will now make a careful computation of the parallax of the *Nova* from its nebulosity with due allowance for the phenomenon described above. The following additional suggestions may be found useful:

1. The actual rate of expansion will be to the apparent rate as the versed sine is to the sine of the angle made by the *Nova*, the Earth, and that point of the visible nebulosity which appears to be most distant from the *Nova*. In other words, the "distortion" will be the "extension" times the sine of its angle.

2. If the nebulosity is due to radiations from the *Nova* upon quiescent matter, the apparent radius of the illumination will vary with the distribution and susceptibility of this matter in spaces through which the locus passes.

3. The radius of illumination will also vary, if the *Nova* does not radiate equally in all directions, or if its radiations are not transmitted uniformly.

4. The apparent brightness and apparent radius of the nebulosity may be unduly increased at first, and decreased at the last owing to the faintness of the outer limits of the illumination. This is because the effect on the photographic plate depends on the thickness of the luminous layer as well as on its degree of brilliancy.

5. On the other hand, if the nebulosity be due to reflection from diffused quiescent matter, the radius of the apparent illumination may be much reduced at first, owing to poor reflection when the rays are received and reflected at such an obtuse angle.

6. The direct method, which involves the assumption that the sine of the "extension" is unity, may give correct results when the *Nova* has ceased to expand, because the actual and apparent radii of the illumination will coincide. The method will be very inexact in application, however, because it will be almost impossible to determine by direct observation the exact period when the nebulosity ceases to expand, owing partly to the irregularity and continuous backward motion of the image, and more particularly to the fact that the rate of expansion is so minute at the end.

7. The very fact that the nebula does not expand or contract appreciably for some time when near its maximum should enable an observer to find the maximum radius of the illumination from a great number of observations, and therefore with satisfactory accuracy.

8. The date of first appearance of the nebulosity should be determined with the greatest possible precision. I believe that it has generally been assumed that the nebulosity around *Nova Persei* began to expand on the night of February 21 to 22, 1901, when the *Nova* was first observed by Dr. Anderson, of Edinburgh. It is not at all certain that this assumption is correct, as it is not proved that the emanations causing the surrounding space to become luminous began at the time of the greatest magnitude of the *Nova*. Accuracy at this point is important, because the rate of apparent expansion is so very rapid at first.

9. It will be observed that the assumed values for the

intensity of the primary emanations given in the first part of Table II agree roughly with the observed visual magnitude of *Nova Persei* at monthly intervals. On reference to Figs. 2, 3, and 4 we see that the area of the visible nebulosity under this assumption is very small. The second assumption, which is merely a random example, gives an outline agreeing somewhat better with the observed nebulosity. It is therefore apparent that an objection to the theory of reflection of ordinary light lies in the observed persistence of certain definite forms in the nebulosity. Of course, a very thin luminous paraboloidal cup, moving with from half to full velocity of light, should show rapid changes in the visible formations.

This distortion phenomenon will affect the image of a nebulosity regardless of the actual nature of the primary emanations. It will affect the image even when the emanations are not radial or not of uniform velocity.

The purpose of this article is merely to describe some of the characteristics of this phenomenon. I hope that it may contribute toward a solution of the problems of *Nova Persei*, and ultimately find a wider application.

BALTIMORE, MD.,
January 1904.

THE ABSORPTION OF RADIATION BY THE SOLAR ATMOSPHERE AND THE INTRINSIC RADIATION OF THAT ATMOSPHERE.

By FRANK W. VERY.

IN 1877 Dr. H. C. Vogel showed by his spectrophotometric measures at different points in the solar image that the absorption exercised by the solar atmosphere on light from the photosphere decreases somewhat regularly from the violet toward the red end of the spectrum; and it is now known that the same law continues far out into the infra-red. While there are some exceptionally strong absorption lines in the violet and ultraviolet part of the solar spectrum, it is evident at once that their number is insufficient to account for the large increase of absorption in these regions, nor is there such a marked concentration of the Fraunhofer lines toward the shorter wave-lengths as will explain the systematic progression in the absorption coefficients of the solar atmosphere. Moreover, a critical examination of the appearance of the Fraunhofer lines from different parts of the solar disk discloses the remarkable fact that they do not vary appreciably at any point of the unspotted surface, and can have nothing to do with the progressively increasing selective absorption deduced from comparisons of radiation at various radial distances in the solar image. This depletion by the solar atmosphere, which increases as the wave-length diminishes, is therefore properly attributed to selective scattering, or diffraction, by fine particles, and not to any true absorption by gaseous constituents of the media traversed by the rays.

Miss Clerke, in her *History of Astronomy in the Nineteenth Century*,[1] refers to the comparison of the intensity of the Fraunhofer lines at the Sun's limb and from the entire disk, as inferred by Professor Forbes, of Edinburgh, from observations of the annular eclipse of May 15, 1836, as follows:

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[1] Fourth edition, p. 134.

> If the problematical dark lines were really occasioned by the stoppage of certain rays through the action of a vaporous envelope surrounding the Sun, they ought, it seemed, to be strongest in light proceeding from his edges, which, cutting that envelope obliquely, passed through a much greater depth of it. But the circle of light left by the interposing Moon, and of course derived entirely from the rim of the solar disk, yielded to Forbes' examination precisely the same spectrum as light coming from its central parts. This circumstance helped to baffle inquirers, already sufficiently perplexed. It still remains an anomaly of which no satisfactory explanation has been offered.[1]

As it seems to me that a sufficient explanation of the supposed anomaly is not far to seek, I desire to point out that in my research on "Atmospheric Radiation"[2] it is shown that increasing the depth of a radiating gas gives progressively diminishing increments of radiation; that, for example, the maximum efficient radiant depth for the flame of illuminating gas from a Bunsen burner, or from a series of such burners, cannot be much over 20 cm; that the radiating power of carbon dioxide is not appreciably increased after the depth of the radiating layer of gas surpasses 90 cm; and that, in general, the depth of the efficient radiating layer of a gas amounts to only a few meters in the case of the feeblest radiators. Consequently, the radiation of a gas is limited by the self-absorption which the gas exercises on its own radiation, proceeding from inner depths of the gaseous mass; and similarly, the line-absorption produced by a gas does not increase indefinitely with the depth, but after a certain mass of the gas has been traversed, all the lines capable of absorption by this gas are stricken out from the spectrum, and the remaining rays pass freely.

Radiation from glowing chromospheric masses of incandescent hydrogen, thousands of kilometers in depth, is still a comparatively superficial affair. Some increase of the total emission must occur, however, from the integration of radiation proceeding from successive layers of chromospheric substance appertaining to different levels, because the deeper layers are usually at higher temperature and pressure, and under these conditions the vibrations of the incandescent particles are damped and distributed through a wider range of frequency. Even if it should be proved that the wide, hazy fringes attending many of the lines, especially those which are prominent in the chromospheric spectrum, are due to anomalous dispersion, the darkest, and distinctly, or suddenly, accentuated central cores must be attributed to absorption. The monochromatic spectral images from the deeper layers are broadened, and the rays corresponding to the outer margins, which the lines then assume, pass unimpeded through the more elevated layers of rarer gas whose particles vibrate within narrower limits. But the rays which represent the cores of the spectral lines, and which proceed from the deep layers, are entirely absorbed by the outer layers with whose periods they are completely in tune. Since the outer strata of the atmosphere are at a lower temperature, their emission of core rays is feebler, and cannot compensate those rays of the deep-layer emission which are absorbed. The double-shouldered lines of the flash spectrum have been explained by Jewell on this principle, but are equally well accounted for on the supposition that the wings are due to anomalous dispersion, as has been shown by Julius.[1] The broadening of the spectral lines from absorption by chromospheric layers having a wide range of pressure does not infringe the general principle that each element, or corresponding pair of elements, of a spectral line is due to a layer of small depth. Because of this small depth of material concerned in the production of the Fraunhofer lines, it makes almost no difference whether the local origin of the rays is near the center or at the margin of the solar disk. As far as the Fraunhofer lines are in question (for a reason which will be mentioned presently), it appears certain that at all points of the Sun's photospheric surface, and for every sort of material, the depth of overlying atmosphere is always more than enough to produce the full amount of absorption which can result with the given pressures and temperatures. If the relative amount of a particular ingredient changes, the variation in the proportional part of the pressure, due to this substance, will involve a change in the breadth and intensity of its spectral lines. To such changes, the peculiarities observed in the spectra of Sun-spots may be partly attributed; and in like manner an alteration in the depth and total pressure of the layers above the photosphere is sufficient to account for many of the variations noted in the different classes of stellar spectra without the need of supposing extensive diversities of composition.

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[1] *Phil. Trans.*, 126, 453.

[2] *Bulletin G, U. S. Weather Bureau*, p. 62.

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[1] Astrophysical Journal, 15, 28-37, 1902.

The failure of the Fraunhofer lines to become intensified at the Sun's limb is to be attributed chiefly to the corrugation of the photospheric surface, and to the fact that the efficient absorbing layer is of a depth not great in relation to the vertical dimensions of these irregularities. That part of the solar atmosphere which produces the line-absorption is a relatively shallow layer whose section in the line of sight is, on the average, approximately the same for all parts of the solar disk. The greater part of the central radiation comes from the depressed surfaces, and has traversed, before arriving at the level of the summits of the photospheric elevations, enough absorbent material to experience about the same line-absorption as the marginal rays which proceed almost wholly from the tops of the photospheric clouds. The selective depletion of radiation by diffraction, on the other hand, increases very rapidly near the limb, proving that this part of the loss comes from the action of a deeper atmosphere, compared to which the dimensions of the irregularities are of less importance, although they are by no means without influence.

It seems to me that the invariability of the Fraunhofer lines is sufficiently explained on these principles. The general absorption which produces the darkening of the Sun's limb has nothing to do with the Fraunhofer lines, but is to be explained in the same way as that part of the depletion of solar rays in passing through the terrestrial atmosphere which comes from the scattering of sky light.

In Professor Schuster's article "The Solar Atmosphere"[1] a considerable portion of solar radiation is assumed to come from an absorbent and radiating layer, distinct from and immediately above the photosphere, and the apparent change of absorption at different distances from the Sun's limb is explained as due to the varying relative preponderance of the two sources—photosphere and atmosphere—in producing the radiation. The symbol I is used for photospheric radiation, and F for "the radiation of a perfectly black body which is at the temperature of the shell' constituting the absorbing atmospheric layer. This supposition implies that the absorbent matter consists of perfectly black particles suspended in a medium. The medium, as a whole, cannot radiate like a perfectly black body, for in this case it would also be perfectly opaque to the photospheric radiations presented for transmission. On p. 326[1] it is said that "there is no reason to look for a different region in the Sun's surroundings for the cause of the observed diminution of radiation, than that which gives the Fraunhofer lines;" and it is inferred that "the layer which gives the line absorption absorbs also to some extent all wave-lengths extending from infra-red to violet."

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[1] ASTROPHYSICAL JOURNAL, 16, 320, 1902.

It will be seen that great importance is attached to the black absorbent particles as radiators, and that no use is made, in this theory, of particles which scatter the photospheric rays selectively. This view is partly supported by those eclipse spectrograms which indicate the presence of incandescent particles giving a continuous spectrum, and no sensible spectrum crossed by Fraunhofer lines, at least in the inner region of the corona, although Professor Schuster does not avail himself of this evidence, and indeed excludes it by limiting his radiant shell to the reversing layer which gives the Fraunhofer lines. In spite of the spectrograms mentioned (which are perhaps not conclusive in their evidence, because a small addition of continuous spectrum makes the Fraunhofer lines difficult to detect), it has seemed to me that there must be depletion of the photospheric radiation by selective scattering from fine particles taking place somewhere in the Sun, because the solar atmosphere limits the spectrum at the ultra-violet end nearly as the Earth's atmosphere does, namely, at a wave-length of about 0.3 μ. The crowding of the solar Fraunhofer lines at the shorter wave-lengths also contributes something to the effect, but here I shall confine myself to depletions which are not in the nature of line-absorptions.

Professor Schuster's theory appears to demand that the coefficient of transmission (called Z in his notation) shall be about the same for all wave-lengths and his computation assigns nearly equal values for Z in the red and the violet. Anyone who has compared the strongly contrasted colors — blue at the center and reddish-brown at the limb of the Sun — will recognize that, if this explanation is to be accepted, the radiation at the limb must come almost entirely from the red-hot particles of the envelope, while the blue-hot photosphere is mainly in evidence at the center; and the absorption by the outer shell must be the general or non-selective one produced by opaque particles too coarse to give much of any selective reflection.

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[1] *Loc. cit.*

It is a fact that, at the photospheric level, some form of matter exists which does radiate indiscriminately through a wide range of wave-length, and whose particles are presumably coarse enough to act non-selectively in other respects. But immediately above the photosphere this quality disappears, to all appearance absolutely, suggesting that the conditions here do not permit the existence of the material out of which photospheres are made, unless in some excessively attenuated form, while the purely bright-line spectrum of the reversing layer further suggests that the medium at the higher altitude resembles the blue flame of a Bunsen burner, in that its particles, being in a state of atomic, or perhaps ionic, resolution, are too small to scatter the rays. If we form an image of the Sun by a powerful condensing lens on a Bunsen flame, it can scarcely be detected; but turn off the air at the base of the burner, restoring the illuminating quality to the flame, and at once you will see a dazzling bluish image of the Sun projected on the flame. The light has here been selectively scattered by fine particles, but by particles much coarser than any which exist in the blue flame. It would seem that if the solar atmosphere contains particles capable of producing such scattering effects, they must be in the photosphere itself, or in some exceedingly thin layer immediately in contact with its surface, possibly an attenuation of its substance, and not simply in a layer as thick even as the chromosphere. Higher up, coarse particles exist only as rare strangers. Still higher up, coarse particles cannot float quiescently, although such particles may be temporarily present while in swift transit, either because they are electrified and repelled, as is suggested by the trumpet forms of coronal extensions, and by the general agreement of the filaments with such forms as streams of electrified particles assume under magnetic control, or because the particles have been mechanically expelled from the Sun and are passing out along orbits, perhaps to merge in the nebulous zodiacal light. In any case, these moving particles must be sparsely distributed, and a great depth of such a dust-laden medium, or of such dust-sown space, will be needed to produce an appreciable effect by intercepting rays of light.

Suppose, however, that we grant the existence of a thin layer having the properties of Schuster's absorbing medium. Will it be distinguishable from the photosphere, and will it fulfil the requisites of his theory?

As no substance is absolutely black, or opaque, through more than a limited range of the spectrum, there are spectral regions where particles of such opaque substances cease to absorb or radiate, and where, consequently, the photospheric radiation may be able to penetrate the hypothetical atmosphere readily. Professor Schuster's analysis shows, however, that, owing to the compensation which results from his theory, parts of the spectrum where the absorption is very great cannot be discriminated from those where the absorption is very small. This follows from the equation:

$$A = (I - F)\, Z^{\sigma} + F,$$

where the mean value of F (the dispensable energy of the envelope which can appear as intrinsic radiation) increases as the transmissive power of the solar atmosphere (Z) diminishes. Hence "constancy of radiation for different distances from the Sun's limb may be due either to smallness of the coefficient of absorption, in which case the radiation is everywhere equal to I, or to its greatness, in which case the radiation is everywhere equal to F, or finally to the near equality of I and F." The argument, like some others appertaining to the subject, is of the inconclusive sort.

Let us suppose, however, that the absorbent medium is not so dense but that a considerable amount of photospheric radiation can penetrate it, and that it supplies a radiation of its own at a lower temperature. This is the main point of Schuster's theory, which requires the combination of spectra whose energy-curves have widely separated maxima. The photosphere has a columnar structure, best seen when dissected in the penumbra of Sun-spots. This structure indicates strong ascending and descending currents, such as we should expect to find produced by convection when the masses of matter, cooled at the surface of the radiating photosphere, seek their level. In the Earth's atmosphere a few degrees, difference of temperature, not often more than 30°, is sufficient to induce the convectional overturnings of the most severe local storms or tornadoes. Bigelow[1] calculates that under solar conditions a few hundred degrees' fall of temperature may be expected in passing through the photosphere. The argument assumes that the photosphere is a condensation-cloud, which seems permissible. If the fall of temperature of a few hundred degrees is sufficient to account for violent movements within the photosphere, however, it is still not great enough to give, at the high temperature of the Sun, more than a very small change in the wave-length of the maximum ordinate in the spectral energy-curve, and not enough for Schuster's explanation of the variation in the apparent solar absorption by which the marginal regions seem more transmissive. Unless it can be shown that there is a probable fall of temperature of some thousands of degrees within this narrow region, this objection greatly diminishes the efficiency of the process proposed by Schuster as the sole one needed. I think we must conclude that no mere skin-layer of attenuated photospheric material is competent to absorb and radiate in the manner required.

My reasons for assuming that the intrinsic radiation of the envelope is relatively small have been founded on Abbot's observation that the corona is "giving light in a manner not associated with a high temperature, or at least with the preponderance of infra-red rays," coupled with Perrine's statement that coronal light resembles sky light, from which we may conclude, I think, that there is a selective scattering of the shorter waves of ether by the solar coronal envelope whose particles are too small to affect the longer infra-red rays. This, taken in conjunction with the apparent cessation of the solar spectrum at about $\lambda = 0.3\mu$, after allowing for the great absorption by the Earth's atmosphere in this region, seems to indicate that the depletion of photospheric radiation by the solar atmosphere, aside from the line-absorption, resembles the action of the Earth's atmosphere in being largely due to selective scattering principally of short waves by fine particles; and this characteristic of the outer and more transparent regions of the solar atmosphere presumably continues and is reinforced in the denser layers.

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[1] *Eclipse Meteorology*, etc.

A further reason for assuming that the general intrinsic radiation from a very thin absorbent envelope is a relatively small quantity is that the brightness of the general spectrum, just outside the Sun's limb, is only a small fraction of the brightness of the photospheric spectrum, in spite of a large admixture of bright photospheric light diffused into the neighboring chromospheric region by our hazy atmosphere. With a slit 1 mm wide, held tangent to the Sun's limb, and with a large dispersion, the general chromospheric spectrum is about as bright as the photospheric spectrum with a slit 0.01 mm wide. The dilution of the spectrum by diffuse sky light possibly constitutes nine-tenths of the light observed. Hence the general chromospheric spectrum is perhaps one-thousandth as bright as the spectrum of the photosphere; that is $F = 0.001 \times I$, instead of $F = I$, or at the least, and for the visible spectrum, $F = \frac{1}{3} \times I$, as Professor Schuster is obliged to assume.

In the flash spectrum of the reversing layer, selective radiation, reinforced by anomalous dispersion, immensely preponderates over general radiation; yet the total of selective and general radiation falls far short of that from the photosphere. Consequently, while the process investigated by Professor Schuster no doubt exists to some extent, and while its effect in producing an apparently greater transmission of the marginal rays is in the same direction as that of other causes enumerated in my earlier paper,[1] and must be added to them, it seems to constitute only a minor part of the complete series of causes, and the seat of its action does not appear to reside exclusively in a thin shell, practically coincident with the reversing layer. The efficient radiating layer is probably deeper than the inner corona, but is nevertheless of comparatively limited depth. Two to eight minutes of arc from the Sun's limb are the limits assigned by the spectrograms of the Lick Observatory eclipse expeditions. Selective scattering, on the other hand, is not only not confined to such a thin layer, but acts from fine particles suspended at levels where the atmosphere is too rare to support the coarser particles which radiate, but are not able to act selectively on the passing rays, as well as from fine particles moving rapidly through free space in the farthest reaches of the outer corona.

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[1] ASTROPHYSICAL JOURNAL, 16, 73–91, 1902.

In view of the arguments in the present paper, it now seems to me probable that the regions very close to the photosphere, and within its interstices, are the ones where something like a thin mist of photospheric material still lingers, and where the principal part of the selective scattering takes place. A wider region, approximately the inner corona, whose spectrum is largely continuous, constitutes the field throughout which the combination of absorption and intrinsic radiation, described by Schuster, acts, the result of the process being much less important than the effect of selective scattering. Finally, the outer corona continues the depletion by selective scattering, but to an extent which is relatively insignificant, and all of the regions have their special discontinuous absorptions and radiations, producing the spectrum of fine lines.

The effect of a scattering medium would seem to be the same as that of an absorbing medium in preventing the escape of radiation from a heated surface, provided the surface radiates the short waves which are scattered by the particles of a certain degree of fineness, peculiar to the scattering medium; but if only long waves are emitted, these are not much scattered by the same medium, and there is no cumulative action by which the retention of radiation will cause the temperature of the surface to mount until short waves are emitted on which the scattering medium can take effect.

On the other hand, an absorbing medium *may* cause a cumulative retention of heat; hence there is a difference between the actions of the two classes of media.

From the depths of the Sun, radiations composed mainly of very short waves tend to proceed, and a very extensive scattering atmosphere acts almost like a reflector, sending nearly all the rays back again. In this case the medium will not be much heated by the process. Only a small fraction of the incident rays will be absorbed by the fine particles; the greater part is by assumption diffracted. Still, as the course of the rays through such an extensive scattering medium is a zigzag one, the scattering being repeated over and over again, some cumulative action and some absorption of energy by the medium must result. Consequently, it is not possible to separate completely the two causes—absorption and scattering.

There is a difference between the action of an extensive and a thin scattering medium. In the extensive medium, or in one densely loaded with the scattering particles, radiation is bandied about so many times before it can escape that a considerable fraction of the energy is absorbed and retained in the medium, thereby raising its temperature, even though the absorbing power of the particles may be small. In the thin medium scarcely any absorption takes place, and the temperature is hardly raised at all, because there is no chance for a long series of recurrent scatterings upon the same luminous energy.

Obstruction to the passage of rays offered by scattering particles will not, in this view, bear any constant proportion to retention of energy by the medium itself. It seems possible to imagine a medium in which there is no absorption whatever, and yet so densely laden with diffracting particles that light might be a long time in getting out of it, that is, in getting reflected back again on its source; for, as Schuster supposes, such a medium would be opaque, and yet the medium would not be warmed by the rays.

The nearly constant radiation of Sun-spots as they approach the limb, for which Professor Schuster gives an explanation according to his theory, is quite as simply explained on the theory of selective depletion of the shorter waves by the Sun's atmosphere. The spot is cooler and gives a greater proportion of radiations of long wave-length, which are more transmissible than those of the general surface.

WESTWOOD, MASS.,
December 1903.

EIGHT STARS WHOSE RADIAL VELOCITIES VARY.

By EDWIN B. FROST and WALTER S. ADAMS.

OUR current observations of stars of the *Orion* type indicate that the following eight stars vary in their velocity in the line of sight. The variation of three of these was suspected[1] from the examination of the plates taken last season with a dispersion of three prisms; but the diffuse character of the lines rendered the measurements with high dispersion very difficult, and with a dispersion of only one prism the determinations are by no means easy or precise.

These measurements, and all others that we have published for stars of the *Orion* type, are to be regarded as merely provisional, since the wave-lengths of certain of the stellar lines (particularly those of silicon) have as yet been only approximately determined in the laboratory, and certain other lines (especially those of hydrogen at λ 4542 and λ 4686) have not been seen in the laboratory. We expect to be able to publish later fairly accurate wave-lengths of these hydrogen lines, as determined from the stars, since we always measure them when sufficiently sharp to be set upon in a stellar spectrum. When we are able to utilize these measures, which we have not yet done, the accuracy of the radial velocities will be appreciably increased.

We defer until a later communication the measures of the velocities of θ^1 and θ^2 *Orionis*, of which we are obtaining as many plates as possible, as the stars promise to be of especial interest. We have been able to secure measurable plates of the other brighter stars of the trapezium besides θ^1, which at the same time yield values of the radial velocity of the *Orion* nebula.

The magnitudes given are from the Revised *Harvard Photometry*.

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[1] ASTROPHYSICAL JOURNAL, 17, 246, 1903.

g Persei ($\alpha = 1^h\ 56^m$; $\delta = +54^\circ\ 0'$; Mag. = 5.0).

Plate	Date	G. M. T.	Taken by	Velocity		No. of Lines		Velocity Mean
				F.	A.	F.	A.	
				km	km			km
IB 176	1903, Nov. 7	$15^h\ 41^m$	F.	−21	−27	3	3	−24
191	Nov. 17	12 56	A.	−19	−21	3	3	−20
200	Dec. 1	13 43	F. A.	−13	−10	3	4	−12
260	1904, Jan. 23	14 45	A.	+8	+12	3	5	+10

The hydrogen lines γ and β and *Mg* λ 4481 are quite sharp in the spectrum of this star, and are well adapted for measurement. The helium lines are not conspicuous. The hydrogen lines at λ 4542 and λ 4686 are present, but faint.

ε Persei ($\alpha = 3^h\ 51^m$; $\delta = +39^\circ\ 43'$; Mag. = 3.0).

Plate	Date	G. M. T.	Taken by	Velocity		No. of Lines		Velocity Mean
				F.	A.	F.	A.	
				km	km			km
IB 180	1903, Nov. 7	$19^h\ 38^m$	F.	−3	−5	4	4	−4
192	Nov. 17	13 36	A.	−26	−30	3	5	−28
202	Dec. 1	15 20	F. A.	−29	−19	4	3	−24
228	Dec. 26	19 3	F.	+15	−3	3	4	....
261	1904, Jan. 23	15 23	A.	−18	−2	3	5	....

In this spectrum the hydrogen and helium lines are broad and diffuse, and the two plates taken in 1901 with three prisms offered little hope of successful measurement. There is a considerable difference in the appearance of the same lines on the different plates of series IB, and it is quite likely that the lines are complex. This gives the effect of maxima of intensity within the broad lines, and in some cases the two observers have evidently not set upon the same point in a line, whence the resulting radial velocities for the two observers are quite widely discrepant. The combination of the results into a single mean would in such a case evidently be incorrect, as the lines dealt with are not the same for the two observers. Accordingly, where instances of this sort are encountered, as in IB 228 and 261 of the table above, we have left blank spaces in the mean velocity column. We consider, however, that the range shown by the other plates of the star is sufficient to establish the variation, quite apart from the evidence in the same direction afforded by the complexity and changes in the lines themselves.

θ^1 *Orionis* ($\alpha = 5^h\ 30^m$; $\delta = -5°\ 27'$; Mag. $= 4.8$).

The measurement of the hydrogen lines in the spectrum of this star is complicated by the superposition of the bright nebular lines. A similar effect is apparent at the helium line λ 4472, where at least one bright line is present, and there is some evidence of further complexity, although in this case the bright line may belong to the star and not to the nebula. We shall discuss this matter, as well as other interesting features of the spectrum of this star and other stars in the trapezium, in a later paper.

The range in velocity which we have so far found for this star amounts to over 60 km.

θ^2 *Orionis* ($\alpha = 5^h\ 30^m$; $\delta = -5°\ 29'$; Mag. $= 5.3$).

This star is Bond 685, and follows the trapezium about 6^s, south 100′. The hydrogen and helium lines are broad and diffuse, and hard to set upon, though not complicated by nebular lines. A range of about 140 km in the radial velocity is indicated on the first four plates. The details of the measurements will be communicated later.

σ *Orionis* ($\alpha = 5^h\ 34^m$; $\delta = -2°\ 39'$; Mag. $= 3.8$).

Plate	Date	G. M. T.	Taken by	Velocity		No. of Lines		Velocity Mean
				F.	A.	F.	A.	
				km	km			km
IB 210	1903, Dec. 1	$20^h\ 55^m$	F. A.	+17	+20	3	4	+18
222	Dec. 25	20 28	A.	+31	+38	3	3	+35
250	1904, Jan. 2	18 14	A.	+16	+11	5	4	+14

Two plates of this star taken early in 1903 with a dispersion of three prisms led to a suspicion of variability in its velocity. The plates, however, were not well adapted to measurement, and no attempt was made to measure them in other than an approximate way. In the list given above all of the plates are noted as good. The spectrum is characterized mainly by the strength of its helium lines, which are, in most cases, fairly well defined. There appear on one or two plates to be evidences of complexity in the spectrum, but these are scarcely sufficient to justify conclusions on the subject.

ξ Orionis ($\alpha = 6^h\ 6^m$; $\delta = +14^\circ\ 14'$; Mag. = 4.4).

Plate	Date	G. M. T.	Taken by	Velocity		No. of Lines		Velocity Mean
				F.	A.	F.	A.	
				km	km			km
IB 184	1903, Nov. 7	$22^h\ 53^m$	F.	+13	− 8	3	4	....
264	1904, Jan. 23	17 47	F. A.	+46	+34	3	5	+40
275	Jan. 29	15 8	A.	+18	+18	4	4	+18

In the case of this star also the first evidences of variability were furnished by two plates taken early in 1893 with a dispersion of three prisms. Under high dispersion, however, the lines in the spectrum are so excessively diffuse and vague as to render measurement practically impossible. The plates taken with one prism which are entered in the list above show a very great improvement in this respect; yet, in spite of this, accurate measurement is extremely difficult, and the results given are subject to considerable uncertainty.

S Monocerotis ($\alpha = 6^h\ 36^m$; $\delta = +9^\circ\ 59'$; Mean Mag. 4.6).

Plate	Date	G. M. T.	Taken by	Velocity		No. of Lines		Velocity Mean
				F.	A.	F.	A.	
				km	km			km
A 307	1902, Jan. 8	$20^h\ 15^m$	A.	+35	+32	3	3	+33
B 276	Jan. 16	15 41	A.	+25	+34	3	3	+28
A 437	1903, April 10	15 7	F. A.	+31	+41	2	4	+36
IB 180	Nov. 14	23 23	A.	+22	+17	3	3	+19
230	Dec. 27	15 34	A.	+ 8	+14	3	3	+11

The investigation of the spectrum of this well-known variable star was begun by us about two years ago, but the variation in its velocity was not established with certainty until quite recently. The spectrum is characterized by broad, strong helium lines, traces of a few oxygen and nitrogen lines, and by the prominence of the two lines of hydrogen at λ4542 and λ4686. The last two lines have been measured upon all of the plates, and when we have more accurate values of their wave-lengths their use will assist materially in increasing the accuracy of the velocity determinations. The results given above may, accordingly, be modified sensibly when these lines come to be included. We are not as yet in possession of sufficient data to draw any conclusions as to the relation between the period of the light variation and that of the velocity variation.

η *Hydrae* ($\alpha = 8^h\ 38^m$; $\delta = +3^\circ\ 46'$; Mag. = 4.3).

Plate	Date	G. M. T.	Taken by	Velocity F.	Velocity A.	No. of Lines F.	No. of Lines A.	Velocity Mean
				km	km			km
B 490	1903, Feb. 4	$16^h\ 56^m$	F.	+5	+2	3	3	+4
IB 214	Dec. 1	23 20	F. A.	+10	+1	5	5	+6
225	Dec. 25	23 22	A.	+26	+26	6	6	+26

We expressed, in March 1903, our suspicion of a variation in the velocity of this star. This has been confirmed by our recent plates. Among the early plates, three, which were obtained under very unfavorable conditions, were too weak for more than rough measurement, and are not included in the list above. The spectrum is difficult of measurement, and there appear to be evidences of the presence of maxima in some of the lines.

The plates measured by Frost in this paper were reduced by Miss Emily E. Dobbin.

YERKES OBSERVATORY,
February 8, 1904.

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The scope of the ASTROPHYSICAL JOURNAL includes all investigations of radiant energy, whether conducted in the observatory or in the laboratory. The subjects to which special attention will be given are photographic and visual observations of the heavenly bodies (other than those pertaining to "astronomy of position"); spectroscopic, photometric, bolometric, and radiometric work of all kinds; descriptions of instruments and apparatus used in such investigations; and theoretical papers bearing on any of these subjects.

In the department of *Minor Contributions and Notes* subjects may be discussed which belong to other closely related fields of investigation.

Articles written in any language will be accepted for publication, but unless a wish to the contrary is expressed by the author, they will be translated into English. Tables of wave-lengths will be printed with the short wave-lengths at the top, and maps of spectra with the red end on the right, unless the author requests that the reverse procedure be followed.

Authors are particularly requested to employ uniformly the metric units of length and mass; the English equivalents may be added if desired.

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ON STANDARDS OF WAVE-LENGTHS.

By H. KAYSER.

WHEN Rowland published his table of standards, the forward step appeared so great, the accuracy and the instrumental means of so high an order, that we seemed to have in hand the foundation for all measurements for many years, perhaps forever. But this hope was shaken when Michelson determined the wave-lengths of three *Cd* lines. That the absolute values differed from Rowland's by 0.2 tenth-meter was of little importance, and could astonish nobody having read critically the determinations made with the grating by Müller and Kempf, Kurlbaum, and Bell, as they clearly show the impossibility of attaining with the grating an accuracy exceeding 0.1 tenth-meter; but the relative differences were unexpected:

Michelson - -	λ 6438.472	5085.824	4799.911
Rowland - -	6438.680	5086.001	4800.097
Difference - - -	0.208	0.177	0.186

These differences are not proportional to the wave-lengths. If the second line is relatively correct, the two other differences should be 0.222 and 0.166; *i. e.*, the first line of Rowland is by 0.014 too low, the third line by 0.020 too high, while according to Rowland we should expect to find no errors exceeding 0.005 tenth-meter.

It seemed possible, however, that only a few lines from Rowland's table had a larger error, and that unfortunately the *Cd* lines were of this kind, but that nevertheless the relative accuracy for the whole spectrum was that given by Rowland.

Now came the absolute determinations by Perot and Fabry of a great number of iron and Fraunhofer lines, made by the much more accurate interference method, and based upon Michelson's *Cd* lines. They show that Rowland's measurements are not nearly so correct, relatively, as we had supposed, and that his system is not sufficient for our needs. With a correct system of standards we could now determine the wave-lengths of all the sharp lines—and 99 per cent. of all the lines can be got sharp—with an accuracy of a few thousandths of an Ångström unit. I am sure that the much larger differences found by different observers are caused very often by the use of different, relatively incorrect, standards.

From extensive use of Rowland's tables I had long ago found that his system is less correct than was generally supposed, and I had tried to amend it. I think that my standards from the iron arc are better, but of course they have the same general feature as Rowland's standards, as will be evident by my method of working, so that alternating parts with positive and negative errors must be common to both systems.

It seems urgent, therefore, to get better standards, as most of the measurements made up to this time with Rowland's standards will prove useless as far as the wave-length is concerned. But before beginning with such a task we must know what were the errors committed by Rowland, that we may avoid them, and we must carefully consider the easiest and most exact way to get better results.

It is quite clear that Rowland's *measurements* have not been erroneous, as his plates, his measuring machine, and his and Mr. Jewell's ability were first-rate. The method of *using* the measurements, therefore, must have been erroneous. I think there are two causes for the bad results: Rowland did not know the difference between the position of solar and arc lines. Even the first step, taking the solar D lines for the arc spectra, was doubtful. We do not know exactly how Rowland's computations were made, but Mr. Jewell says:

> As Professor Rowland was not convinced that the displacement was due to any other cause than the accidental movement of the apparatus, when changing from the spectrum of the Sun to that of the arc, the displacement was treated as due to this cause, and the wave-lengths of all metallic lines corrected for the average displacement of the stronger "impurity lines" (generally iron) upon the plate, thus reducing them to an approximate agreement with the corresponding solar lines.[1]

Rowland has thus shifted different parts of the spectrum to smaller or greater wave-lengths, and as from such parts by the method of coincidences other parts have been determined, perhaps with another shifting, it is impossible to know to what extent the errors may have accumulated in different parts.

If this were the only cause of error, it would be easy to avoid it. We should then again apply the method of coincidences, but using exclusively arc lines and using as basis one, or better all, of the lines determined by Fabry and Perot. It is true that we cannot be quite sure of the correctness of these measurements. After reading all the papers of Perot and Fabry, I am personally inclined to believe their numbers exact; but as this can be rendered certain only by new measurements, Dr. Eversheim has undertaken this task in my laboratory by using Perot and Fabry's method and apparatus.

But there may be yet another cause for the inaccuracy of Rowland's results. As it is impossible to get exact absolute measurements with the grating, the method of coincidences also may have led to errors. Indeed, Michelson has lately shown that an error in the ruling of gratings is possible which falsifies the results of this method, and there may be other causes not yet found with the same effect.

Therefore the applicability of the method of coincidences with Rowland's grating must first be tried. It seems possible to test at the same time the exactness of Perot and Fabry's numbers. If we go by the method from one line of Perot and Fabry to another of their lines, and if we so find exactly their numbers, it seems very improbable that both this method and their numbers are false, and that the two errors have exactly compensated one another; we should rather conclude that method and numbers are right. If, on the other hand, we find other numbers than those of Perot and Fabry, either these numbers, or the method, or both, may be erroneous.

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[1] ASTROPHYSICAL JOURNAL, 3, 89–113, 1896.

I have two of Rowland's largest concave gratings of 21 feet radius and 5.5 inches breadth, the first ruled on Rowland's third engine with 16,000 lines to the inch, the second ruled on the second engine with 20,000 lines to the inch. With the first grating Dr. Konen prepared for me plates containing Perot and Fabry's lines at λ 5302 and 5434, in the second order, coinciding with λ 3550 to 3630 in the third order. The wave-lengths of the lines in the third order were determined from Perot and Fabry's lines. Then other plates were procured containing these lines in the fourth order; on them appear at the same time Perot and Fabry's lines at λ 4736 and 4859 in the third order, so that their wave-length could be determined. I found in this manner, for instance, 4736.804, instead of Perot and Fabry's number, 4736.785. As the different measurements on different plates agree for the same line to 0.003 Å, it is obvious that either the grating is not to be used for the method of coincidences, or Perot and Fabry's numbers are not correct.

I then used the second grating. The line of Fabry and Perot λ 4859 in the second order gives the wave-lengths near λ 3240 in the third order. If λ 3240 is then photographed in the second order, we get Fabry and Perot's lines 6495 in the first order. I obtained in this manner in the first position the wave-lengths:

			Mean
3230.922	.923	.920	.922
3233.008	.009	.005	.007
3236.180	.178	.179	.179
3239.392	.394	.390	.392
3244.160	.160	.159	.160
3245.942	.940	.935	.939
3246.921	.919	.919	.920
3248.162	.160	.158	.160

Determining from these lines on the second plate the line 6495, I got 6494.884, whereas Perot and Fabry have 6494.992.

The difference, 0.108 Å, is much greater than for the first grating, but the conclusion to be drawn is the same.

I finally compared the two gratings directly. With each grating two plates of the region λ5302 to λ5434 in the second order were procured and the lines of the third order determined. I thus obtained the following numbers:

Grating with 20,000 Lines			Grating with 16,000 Lines			Difference
First Plate	Second Plate	Mean	First Plate	Second Plate	Mean	
3541.068	.069	.069	.103	.101	.102	0.033
3553.716	.719	.718	.756	.751	.754	0.036
3558.494	.493	.494	.532	.531	.532	0.038
3565.356	.361	.359	.396	.393	.395	0.036
3570.078	.082	.080	.117	.113	.115	0.035
3586.966	.965	.966	.003	.002	.003	0.037
3606.667	.663	.665	.697	.696	.697	0.032
3608.845	.841	.843	.879	.876	.878	0.035
3617.782	.778	.780	.805	.809	.807	0.027
3621.452	.447	.450	.478	.477	.478	0.028
3621.996	.991	.994	.019	.019	.019	0.026

By the difference of nearly 0.03 Å, it is evident that the two gratings give different results, and that they both are not to be used for the coincidence method. The slow decrease in the differences is occasioned by a weak line of the third order coinciding so nearly with the line 5302 on the plates from the first grating that it falsified this measurement, while on the plates from the second grating the lines were separated enough.

It seems, therefore, that we have no reason to doubt the accuracy of Perot and Fabry's values, but that the method of coincidences is not applicable for my gratings. Perhaps there may exist gratings free from this fault, but every one must be carefully tested before using.

I have then no means for procuring a better system of standards, as I had hoped to do by application of the method of coincidences on all the lines measured by Perot and Fabry. The only possibility of getting such standards seems to lie in the absolute determination by the interference method of one or two dozen more lines in the ultra-violet, between which other lines could then be interpolated from concave grating photographs.

Bonn, February 1904.

SPECTRA FROM THE WEHNELT INTERRUPTER. I.

By HARRY W. MORSE.

NEARLY everyone who has written on the subject of the electrolytic interrupter of Wehnelt has noticed and described the brilliant light which is produced about the "active" electrode when the interrupter is in action. Wehnelt himself[1] examined this light and states that he found in its spectrum lines of hydrogen, the D lines of sodium, and when the active electrode was made negative, many other bright lines. Voller and Walter[2] made a more complete qualitative study of the spectra and found that apparently any metal, when used as active electrode in the Wehnelt arrangement, gave its characteristic spectrum. They speak also of the fact that it was frequently necessary to change the electrolyte, as the metal which had been used in preceding experiments as active electrode contaminated succeeding spectra and showed its own lines together with those of the metal under examination. These same facts have been brought out more fully, though still in a very crude and qualitative way, by Hoppe[3] and Werner von Bolton,[4] both of the latter suggesting the use of the phenomenon for producing colored light and spectra for demonstration. Simon[5] states that in the form of interrupter which he used, in which the break takes place, not at a metal point, but in the electrolyte at a narrow opening in a dividing diaphragm between two large electrodes, the same light-phenomena are produced, but no further data on the spectra are given. Hale[6] examined the spectrum of an iron point in the Wehnelt interrupter in connection with other spectra produced by the arc under liquids. Konen[7] in a paper on the same subject also speaks of these spectra, but appears to consider the light too feeble to permit of photography of the spectrum.

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[1] *Wied. Ann.*, **68**, 233, 1899.

[2] *Wied. Ann.*, **68**, 539, 1899.

[3] *Electrotech. Ztsch.*, **21**, 507, 1900.

[4] *Ztsch. f. Electrochem.*, **9**, 913, November 1903.

[5] *Wied. Ann.*, **68**, 860, 1899.

[6] ASTROPHYSICAL JOURNAL, **15**, 131, 1902.

[7] *Ann. der Phys.*, **9**, 742, 1902.

The present paper contains the first part of a research on the spectra produced by an arrangement similar to the Wehnelt interrupter, with tables of the wave-length and approximate intensities of lines of the following metals, together with comparison tables and plates of lines produced in the arc and condensed spark:

Lithium — Carbon point in solution of lithium chloride.
Sodium — Carbon point in solution of sodium chloride.
Potassium — Carbon point in solution of potassium chloride.
Magnesium — Wire in hydrochloric acid.
Calcium — Platinum point in solution of calcium chloride.
Strontium — Platinum point in solution of strontium chloride.
Barium — Platinum point in solution of barium chloride.
Aluminium — Wire in hydrochloric acid.
Silver — Wire in hydrochloric acid.
Zinc — Wire in hydrochloric acid.
Mercury — Platinum point in solution of mercuric nitrate.
Tin — Wire in hydrochloric acid.
Lead — Wire in hydrochloric acid.

It is the intention to present in this paper the more general study of the phenomena, and those spectra have therefore been selected from the plates at hand which are simplest and show marked points of interest.

At first sight of the phenomenon one is reminded of the production of spectra by allowing the spark to pass from a platinum point *to* a solution of a metallic salt, and the spectra do show marked similarity to those produced in this way. The researches on the mechanism of the interrupter have shown, however, that the breaking of the circuit is caused by the formation of a layer of vapor about the active point, and that the water of the solution is in large measure dissociated by the high temperature reached.[1] There seemed, therefore, the possibility that we might possess in an arrangement of this kind another step in our scale of spectra, and possibly a temperature midway between that of flame and arc, or arc and spark.

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[1] See VOLLER and WALTER, *loc. cit.*

The importance of a more thorough study of spectra produced under water and in gases and vapors under pressure, and the fact that among von Bolton's drawings of spectra of the Wehnelt interrupter there are several which are *banded*, gave interest to a more exact study of the phenomena.

In order to reach some degree of accuracy in the comparison of wave-lengths, the spectra were photographed with a Rowland concave grating of 163 cm radius, of about 2,500 lines to the cm. This grating has a ruled surface of 8 × 14.5 cm, and gives a very bright spectrum indeed. The dispersion is of course small, the length of the first spectrum from λ3200 to λ6000 being only about 5 cm. This grating was kindly loaned us by Professor Langley, and has proved indispensable for the work.

The instrumental arrangements were simple. The Wehnelt cell was made of a beaker, the large electrode was of platinum, lead, or aluminium, and the point was a wire of the metal under investigation, or, where the metal was in solution as a salt, of platinum or carbon. In this latter case the platinum lines or the lines of impurities in the carbons used often appeared, and they were used as standards with which to compare the spectrum sought. The lines of the metal forming the large plate also appeared after a prolonged exposure. The image of the light about the point was focused on the slit by means of a condensing lens of aperture sufficient to fill the whole of the large grating with light.

The exposures required were long, as the light is at best weak compared with that of the spark or arc, of even that of a Geissler tube. For a slit-opening of 0.10 mm the exposure in the first spectrum was from one to two hours. In the third spectrum, where photographs were taken for the more accurate comparison of wave-lengths, the exposure reached six hours, the intensity of the light varying greatly with different metals.

The spectra were photographed on orthochromatic plates, without color screen, and the range of most of the photographs is from λ3200 to λ6000. In some cases the photograph extends much farther into the red, the line of lithium at λ6709 being, for example, clearly visible. The plates were developed with amidol, to which only a very small amount of sodium sulphite and a little potassium bromide were added. This developer acts slowly, but permits of prolonged development without the production of chemical fog. It is to be highly recommended for work of this kind, where under-exposure is the rule and every possible detail must be obtained from the plate.

During the exposure the light was observed frequently with a direct-vision spectroscope, and the various parts of the glowing gaseous envelope about the point were examined in the hope of finding differences in the spectrum at various points. Such differences were not found, the spectrum being apparently the same in all parts of the envelope and remaining remarkably constant throughout the exposure.

As the electrolyte became hot, the intensity of the light became less, and for the sake of economy in time the solution was usually changed every ten or fifteen minutes. The points of most of the metals used also required frequent replacing, and this was done by feeding the wire down through a simple clamp as fast as it was eaten away.

The first series of observations showed that the spectrum is exactly the same, whether the metal in question is used as active electrode or is present as a salt in solution; further, whether the metallic point is anode or cathode, though a great difference in the intensity of the light exists in the two cases. The metallic point as anode gives only a feeble zone of light. As cathode several distinct stages of the condition about the point are to be distinguished, one of these being accompanied by a rapid *Zerstäubung* of the metal. This condition is unfavorable for the production of a bright luminescence, but goes over with increase of current density into the more favorable condition.

It was found that the spectrum is exactly the same whether produced by direct or alternating current. With direct current the electrolyte heated faster and the point was more rapidly eaten away. The greater part of the work was therefore carried out with the commercial alternating current, which is of 110 volts and 60 cycles. The current through the cell averaged 2.5 amperes, and it was found best to keep the resistance of the electrolyte at a point which would give about this current. The large plate had a contact surface of about 10 sq. cm, and the wires used were of diameter 0.3 to 1.5 mm.

No direct experiment on the effect of inductance in the circuit was made, but the cell was used alternately without inductance and as interrupter with a large induction coil for the production of the spark spectra, without any change being visible in the small direct-vision spectroscope.

It was expected that many gaseous lines would appear, and they were looked for, but the only one found under the conditions of the experiment was the red hydrogen line at λ6562.[1] This is visible clearly in many cases; in others it is either very faint or entirely invisible.

In the following tables the wave-lengths of the principal lines are given, with their intensities in the spark, arc, and Wehnelt spectra on a scale of 1 to 100; 1 being the intensity of a barely measurable line, and 100 that of very strong lines like the principal lines of the alkali- and alkaline earth-metals. It is, of course, clear that such intensity measurements with the eye, on plates where the exposures are by no means comparable, are only rough approximations. The attempt has therefore been made to confine any conclusions drawn from such comparisons to cases so obvious and striking that there could be no possible chance of error introduced by difference in exposure or width of slit.

Careful comparison of the spectra produced by a platinum or carbon point in solutions of various salts of the same metal shows that there are no differences whatever corresponding to different salts. This has been proved for zinc by photographing the spectrum of a platinum point in zinc sulphate, nitrate, chloride, bromide, and iodide, and also that of a zinc point in sulphuric, nitric, and hydrochloric acids. These spectra are all identical within the limits of the method. The same has been shown for aluminium for an equally extended series of salts and acids, and in the cases of other metals for a less number of combinations. The tables give the data for a stated combination in each case, but apply equally well to any other for the same metal or for any salt of the same metal.

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[1] WERNER VON BOLTON, *loc. cit.*, used the hydrogen lines of the Wehnelt as standards for comparison, and shows them in his drawings of spectra. Certainly none appear on any of the author's plates.

The present paper is concerned only with the photographs of the Wehnelt in the first spectrum, where comparison can be made with the full spectrum of spark and arc without disturbance from overlapping. The dispersion is only sufficient to give an accuracy of about 1 Ångström unit in the comparison of wave-lengths.

LITHIUM.

(Plate XVII, Fig 1.)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3233.0......	6	10	2	4273.5.......	5	30	5
3795.0......	..	5	..	4602.5.......	100	100	100
3915.0......	..	8	..	4972.0.......	40	50	15
3986.0......	..	8	..	6104.0.......	10	20	30
4132.5......	15	100	10	6708.0.......	..	2 rev	5

Spark—Lithium chloride on carbon electrodes.

Arc—Lithium chloride on carbon electrodes.

Wehnelt—Carbon point in solution of lithium chloride. (The impurities in the carbon are iron, calcium, and aluminium.)

It seems probable that the exposure of the Wehnelt is at least as great in proportion as the others, since the line at λ6708 comes out clearly, and lines of shorter wave-length than λ 3233 are visible.

The resemblance to the spark spectrum is striking, but there are considerable differences in intensities, λ 4972 being much weaker and λ 6104 much stronger. Many of the strong *arc* lines are either absent or greatly reduced in intensity. It is of interest to note that the lines which retain a part of their intensity belong to the principal and first sub-series of Kayser and Runge, while those which lose all or a great part of their intensity from arc to Wehnelt belong to the second sub-series. The lines at λ4972.0, λ4273.5, λ3986.0 are of this latter class.

SODIUM.

(Plate XVI, Fig. 2.)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3303.0......	15	40	10	5688.0.......	15	40	30
4983.0*d*.....	..	10	..	5890.0.......	50	50 rev.	50
5155.0*d*.....	..	4	..	5896.0.......	40	40 rev.	50
5682.5.....	15	15	10				

Spark — Sodium chloride on carbon electrodes.

Arc — Metallic sodium on carbon electrodes.

Wehnelt — Carbon point in solution of sodium hydroxide. (Impurities same as in lithium.)

A rather close agreement with the spark spectrum is to be seen, with a noticable difference in the relative intensities of the lines at λ5682 and λ5688. The lines which are present in the arc spectrum and do not appear in the Wehnelt spectrum belong in this case also to the second sub-series, but it is quite probable that the exposure was insufficient to bring out these relatively weaker lines. λ 5896 is at least as strong as λ5890. Taking into account the rapid decrease in the sensitiveness of the plates in this region, it must in reality be stronger.

POTASSIUM.

(Plate XVI, Fig. 3.)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3217.5......	..	3	..	5340.0.......	2	20	6
3447.0......	..	40	20	5343.5.......	1	..	..
4044.5......	30	100	100	5359.5.......	..	15	6
4047.0......	..	..	..	5783.0.......	3	20	6
5009.5......	..	4	1	5802.0.......	3	20	10
5112.5......	..	3	1	5812.5.......	..	3	1
5323.5.....	2	10	3	5832.0.......	2	10	6

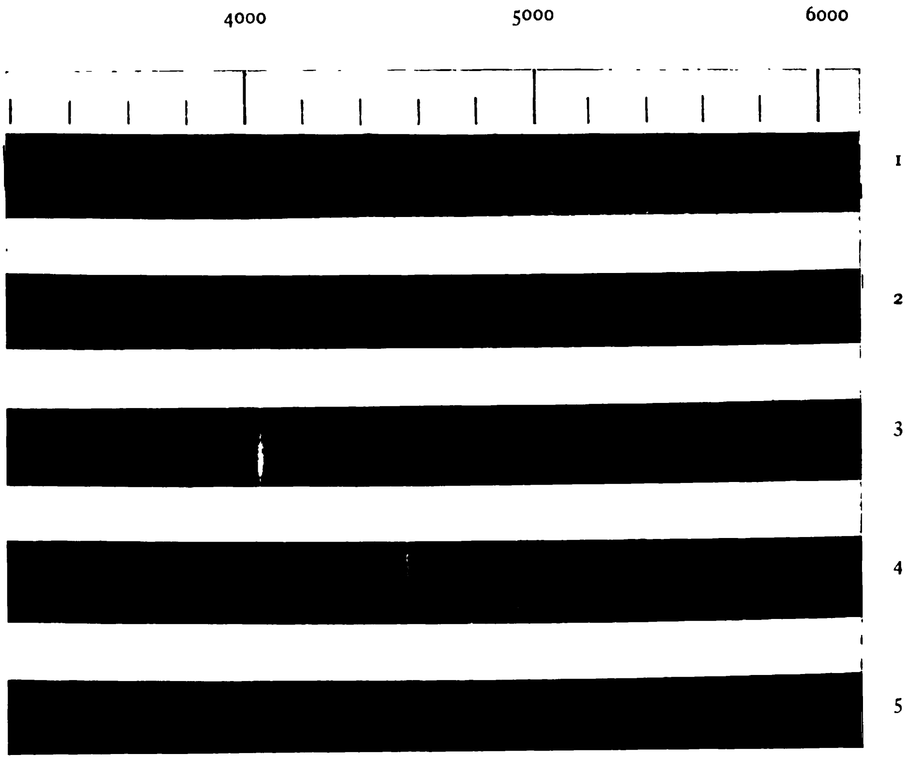
Spark — Potassium chloride on carbon electrodes.

Arc — Metallic potassium on carbon electrodes.

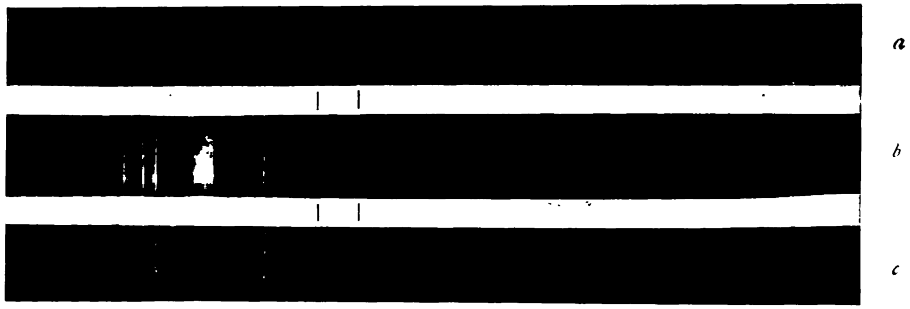
Wehnelt — Carbon point in solution of potassium carbonate. (Impurities in carbons same as in lithium.)

The spectrum resembles the arc more closely than the spark. The difficulty of obtaining the spark spectrum unobstructed by

PLATE XVI.



1. Carbon point in hydrochloric acid.
2. Carbon point in sodium hydroxide solution.
3. Carbon point in potassium carbonate solution.
4. Platinum point in barium chloride solution (impurity, lead.)
5. Platinum point in strontium chloride solution.



6. (*a*) Spark between lead electrodes.
(*b*) Arc. Metallic lead on carbon electrodes.
(*c*) Lead wire in hydrochloric acid.

air lines and the lack of a resolution of the doublets make comparisons in the case of little value.

MAGNESIUM.

(Plate XVII, Fig. 2.)

Wave-Length	Spark	Arc	Flame	Wehnelt	Wave-Length	Spark	Arc	Flame	Wehnelt
3330.0.....	7	8	....	7	4966.5....	..	..	....	4
3332.5.....	10	10	....	10	4974.5....	..	..	....	*b*
3337.0.....	12	15	....	12	4984.5....	..	..	....	*b*
3341.0.....	..	..	....	2	4995.0....	..	..	....	*b*
3437.5.....	15	..	....	..	5006.0....	..	..	....	*b*
3720.0.....	..	..	strong	10	5020.0....	..	..	....	*b*
3724.0.....	..	..	strong	15	5028.3....	..	..	....	*b*
3730.0....	..	..	strong	20	5036.0....	..	..	....	*b*
3829.5.....	20	10	strong	20	5063.0....	..	..	....	*b*
3832.5.....	30	15	strong	30	5072.0....	..	..	....	*b*
3838.5.....	40	20	strong	40	5079.5....	..	..	....	*b*
3855.0.....	..	..	....	1	5086.5....	..	..	....	*b*
4352.0.....	3	12	....	5	5168.0....	..	20	....	20
4443.5.....	..	..	....	b	5172.5....	5	30	....	30
4449.0.....	..	..	....	b	5183.0....	5	50	....	50
4481.0.....	30	..	....	30	5527.5....	4	..	....	3
4570.0.....	..	1	strong	..	5529.0....	..	20	....	..
4704.0.....	4	15	....	6	5711.0....	..	3	....	..
4960.5.....	..	..	....	10	5880.0....	..	..	....	*b*

Spark — Magnesium terminals.
Arc — Metallic magnesium on carbon electrodes.
Flame — Liveing and Dewar's measurements.
Wehnelt — Magnesium wire in hydrochloric acid.

In the above table the following points are of especial interest:

1. The triplet λ 3720, λ3724, λ3730. These lines do not appear in the spark or arc spectrum under ordinary circumstances, but are strong in the spectrum of magnesium in the oxy-hydrogen flame, and have always been considered lines belonging to a low temperature. Liveing and Dewar[1] observed that when the arc passed between electrodes of metallic magnesium, these lines were visible, provided the atmosphere about the arc was one which could provide oxygen. They come out clearly in air, oxygen, and carbon dioxide, but do not appear in hydrogen, nitrogen, cyanogen, chlorine, or ammonia.

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[1] *Proc. R. S.*, **32**, 189, 1881; **44**, 241, 1888.

2. The presence of the arc line at λ 4352 and the strong spark line at λ 4481. One or the other of these is usually very faint under ordinary conditions. In the arc between magnesium electrodes both lines are strong, λ 4481 sometimes quite as strong as in the spark. Hartmann and Eberhard[1] have shown that in the spectrum of the arc between magnesium terminals under water, spark lines become strong, λ 4481 showing clearly. Hartmann[2] has also shown that there is reason to doubt that λ 4481 corresponds to a higher temperature than λ 4352. The spectrum of the arc between magnesium terminals in an atmosphere of hydrogen is nearly identical with that produced under water.

3. The absence of certain strong lines in the Wehnelt spectrum; among these the arc line λ 5529, the flame line λ 4570, the spark line λ 3437.5. The presence of other lines usually appearing, and supposed to correspond to the same temperature, is also of importance.

4. The presence of the bands usually ascribed to the oxide. In the band with head at λ 5006 seven flutings are visible. These are also visible in the arc spectrum, but are much fainter. This band was described by Liveing and Dewar (*loc. cit.*) and resolved into fine lines by Crew and Basquin.[3] The first-named authors obtained the band only in oxygen, air, or carbon dioxide; and the evidence seems to show conclusively that it is due to the oxide. It seems clear from Liveing and Dewar's work that the presence of this band does not necessarily indicate a lower temperature than that corresponding to the other lines of the spectrum of magnesium. This band also appears when the spark is allowed to pass from a platinum point to a solution of a magnesium salt.[4]

5. The *appearance* of certain lines. The line at λ 4481 is perfectly sharp, as it is when inductance is introduced into the circuit of the spark in air.[5] The triplet λ 3829.5, λ 3832.5, λ 3838.5 is very intense, and the lines are broadened and diffuse in contrast with their appearance in air. Wilsing[6] finds that when the

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[1] ASTROPHYSICAL JOURNAL, 17, 220, 1903.

[2] *Ibid.*, 17, 270.

[3] *Ibid.*, 2, 101, 1895.

[4] See LECOQ DE BOISBAUDRAN, *Spectres Lumineux*.

[5] See HUGGINS, ASTROPHYSICAL JOURNAL, 17, 145, 1903.

[6] *Ibid.*, 10, 113, 1899.

PLATE XVII.

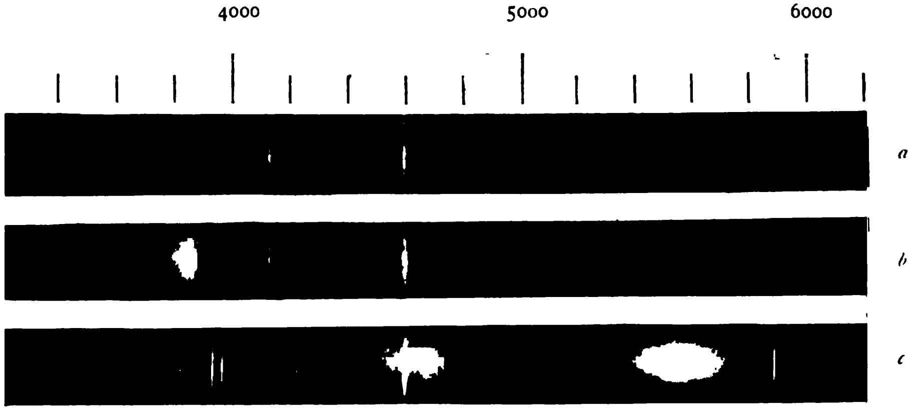

FIG. 1.—(*a*) Lithium chloride. Arc spectrum.
(*b*) Lithium chloride. Spark spectrum.
(*c*) Carbon point in lithium chloride solution.

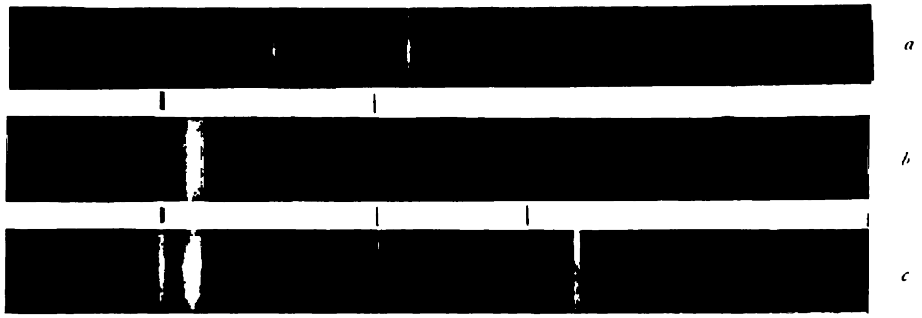

FIG. 2.—(*a*) Spark between magnesium terminals.
(*b*) Arc. Metallic magnesium on carbon electrodes.
(*c*) Magnesium wire in hydrochloric acid.

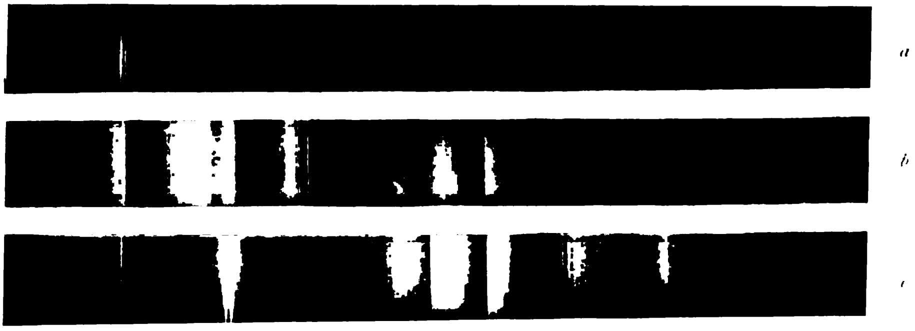

FIG. 3.—(*a*) Spark between aluminium terminals.
(*b*) Arc. Metallic aluminium on carbon electrodes.
(*c*) Aluminium wire in hydrochloric acid.

arc passes between magnesium terminals under water, this triplet is displaced, and broadens out into diffuse absorption bands.

CALCIUM.

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3179.5......	20	..	..	4878.5......	5	8	..
3275.0......	..	8	..	5041.5......	3	4	..
3631.0......	5	30	2	5189.0......	3	4	..
3644.5......	10	20	2	5262.5......	3	4	3
3706.5......	50	10	20	5265.7......	2	6	2
3737.5......	50	25	30	5270.5	5	10	..
3933.5......	100	100	60	5349.5......	3	5	..
3968.5......	60	70	40	5472.0......	..	2	*b?*
4227.0......	40	100	30	5509.0......	2	3	*b?*
4283.0......	6	10	5	5537.0......	..	..	*b?*
4289.5......	4	10	5	5582.0......	3	6	*b?*
4299.0......	3	5	3	5589.0......	10	10	15
4302.5......	5	8	8	5594.0......	4	6	*b?*
4308.0......	3	8	3	5598.5......	4	4	*b?*
4319.0......	7	10	3	5601.5......	3	3	*b?*
4425.5......	7	15	3	5603.0......	3	2	*b?*
4435.5......	10	20	8	5857.5......	..	5	4
4455.0......	15	30	15				

Spark — Calcium chloride on carbon electrodes.
Arc — Calcium chloride on carbon electrodes.
Wehnelt — Platinum point in calcium chloride solution.

The spectrum is very like that of calcium in the spark, with many differences of intensity, and absence of some fairly strong lines. The spectrum from λ 5500 to λ 5900 is of interest. There is evident diffuseness in the lines in this region, in marked contrast to the sharp lines of the spark and arc; but whether this is due to a real difference in the spectra or a possible lack of adjustment of the apparatus, a more extended investigation must decide. So far as the plates obtained show, there are bands with heads corresponding to sharp lines in the arc and spark spectra.

STRONTIUM.

The spectrum is in general similar to that of the spark, the order of intensities agreeing well in the majority of instances. A few of the stronger spark lines, with intensities sufficient to make them visible if they were present in normal intensity, are

STRONTIUM.

(Plate XVI, Fig. 5.)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3381.0......	30	8	5	4869.0.....	4	..	..
3465.0......	40	10	20	4874.0.....	5	5	5
3475.0......	10	8	3	4893.0.....	2	..	..
3706.0......	..	10	3	4962.0.....	7	8	3
4030.0......	..	8	..	4968.0.....	2	4	..
4078.0......	100	50	50	5221.5.....	2	..	..
4162.0......	15	5	6	5224.0.....	2	..	..
4215.5......	100	40	40	5238.5.....	2	5	..
4303.0......	..	2	..	5256.5.....	3	5	..
4306.0......	40	4	20	5456.5. ...	3	..	..
4319.0......	..	8	..	5480.5.....	8	..	..
4438.0.....	..	30	..	5485.0.....	1	..	*b?*
4531.5......	..	5	..	5504.0.....	6	..	*b?*
4607.5......	25	50	30	5520.5.....	4	..	..
4722.5......	5	10	5	5534.0.....	20	..	*b?*
4742.0......	5	10	3	5540.0.....	3	..	..
4784.0......	3	8	2	5587.0.....	..	..	*b?*
4812.0......	7	10	6	5850.0.....	4	..	..
4832.0......	6	10	3	5890.0.....	..	..	*b?*
4855.0......	2	..	..	5895.0. ...	..	..	*b?*

Spark—Strontium chloride on carbon electrodes.
Arc—Strontium chloride on carbon electrodes.
Wehnelt— Platinum point in solution of strontium chloride.

not to be seen. Among these are the group λ 5225–λ 5257. The "oxide" bands are bright.

The same question arises here as in the case of calcium. In the Wehnelt spectrum of strontium there are diffuse bands in the yellow and yellow-green with maxima which seem to correspond closely with sharp lines in the spark spectrum. Whether or not greater dispersion will show these to be really bands with heads in the same places as are occupied by sharp lines in the other spectra, the plates at hand give insufficient evidence. A more exact study of these bands and the similar ones in the calcium spectrum offers great interest.

The following comparison table for barium does not include the bands in the green, which are strong in the spectrum of the Wehnelt:

BARIUM.

(Plate XVI, Fig. 4.)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3377.0......	..	8	..	4674.0.....	2	5	2
3420.5......	..	10	6	4691.0.....	1	5	..
3501.0.....	5	15	..	4727.0.....	1	10	..
3525.0......	..	6	..	4900.0.....	30	..	30
3545.0......	..	6	..	4903.0.....	..	10	..
3892.5......	50	8	50	4934.0.....	80	30	100
3910.0......	..	8	2	5160.0.....	..	10	..
3993.5......	5	15	3	5424.0.....	..	40	5
4131.0......	40	40	60	5519.0.....	5	30	6
4166.0......	15	10	15	5534.0.....	20	80	100
4283.5......	..	20	3	5620.0.....	..	10	..
4351.0......	..	20	2	5680.0.....	..	8	..
4403.0......	3	10	3	5778.0.....	..	50	5
4432.0......	3	8	5	5800.5.....	..	10	..
4506.0......	2	4	4	5826.0.....	..	10	2
4525.0......	30	30	30	5854.0.....	8	10	8
4554.0......	100	100	100	6142.0.....	..	2	5
4580.0......	..	5	4				

Spark —Barium chloride on carbon electrodes.
Arc—Barium chloride on carbon electrodes.
Wehnelt—Platinum point in solution of barium chloride.

The following table gives the approximate position of these bands:

BANDS IN THE WEHNELT SPECTRUM OF BARIUM.

Wave-Lengths		Wave-Lengths	
4570.0 to 4575.0		5272.0	(red edge of same fluting)
4598.0 to 4605.0		5325.0	head of fluting (red edge)
5134.0	center of band	5446.0 to 5462.0	
5167.0	center of band	5477.0	center of band
5242.0	head of fluting (violet edge)	5497.0 to 5519.0	(line; intensity 6)

The spectrum produced about a platinum point in a solution of barium chloride is in many points similar to the spark spectrum. Many arc lines, absent from, or extremely weak in, the spark spectrum make their appearance. λ 3910.0, λ 4283.0, λ 4351.0, λ 4580.0, λ 5425.0, λ 5778.0, are examples. At the same time, many strong arc lines are absent in the Wehnelt spectrum, which has the appearance of a rather incomplete composite of arc and spark spectrum, so far as the *line* spectra are concerned. The brightness of the "oxide" bands in the green is remarkable. Altogether the spectrum of the Wehnelt is much like that produced by sparking from a platinum point to a solution of a barium salt.[1]

ALUMINIUM.

(Plate XVII, Fig. 3.)

Wave-Length	Spark	Arc	Wehnelt
3587.0	50	20	25
3602.0	30	4	4
3612.5	15	...	2
3702.5	2	...	...
3714.0	8	...	2
3944.0	50	60	50
3961.5	100	100	100
4034.3		Heads of flutings in arc spectrum	Heads of flutings in Wehnelt spectrum
4083.7			
4243.2			
4262.5			
4271.8			
4274.0			
4276.6			
4279.3			
4282.7			
4306.8			
4332.0			
4341.7			
4354.3			
4371.7			
4375.6			
4384.6			
4395.6			
4414.8			
4432.5			
4448.0			
4464.0			
4472.0			
4480.0			
4495.3			
4512.2			
4517.7			
4530.0			
4538.7			
4558.9			
4577.6			
4595.0			
4608.4			
4625.9			
4642.3			
4648.5		Second band heads	Second band heads
4662.8			
4671.9			
4695.2			
4717.1			
4736.9			
4755.1			
4782.6			
4803.3			
4817.8			
4842.0		Third band heads	Third band heads
4861.0			
4866.6			
4889.6			
4951.6			
4960.1			
4980.1			
4994.0			
4999.5			
5011.0			
5017.8			
5080.6		Fourth band heads	Fourth band heads
5093.3			
5102.7			
5111.4			
5118.1			
5124.0			
5142.6			
5148.0			
5161.0			
5176.0			
5190.0			
5202.0			
5207.6			
5222.4		Bands	Bands
5328.5			
5337.0			
5465.0			
5593.0		5	5 Lines
5697.0		3	3
6234.0		..	3
6244.0		..	5

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[1] See LECOQ, *loc. cit.*

The spectrum of an aluminium point as active electrode in an acid or an alkali or a salt solution, and that from a platinum point in a solution of an aluminium salt, seem to be exactly the same as that obtained by allowing a spark discharge without condenser to pass in air between aluminium terminals. The author has obtained the same banded spectrum in tubes containing oxygen at a pressure of a few millimeters of mercury, and with the same distinctness in tubes containing hydrogen at low pressures, by allowing the spark, condensed or uncondensed, to pass between aluminium terminals. In the case of tubes filled with hydrogen the bands persist for only a comparatively short time, and the spectrum of hydrogen remains. The same spectrum, with the exception of some lines not belonging to the bands, is obtained from aluminium in the arc.

Hasselburg[1] has measured a great number of lines in these flutings, and his measurements have been used for comparison, the agreement being as close as could be expected from the small dispersion and poor definition of the plates measured.

These bands have been for many years attributed to the oxide, but there exists a considerable amount of evidence contradictory to this view. Arons[2] found this same banded spectrum in the arc between aluminium points in an atmosphere of nitrogen or hydrogen, and concluded that the banded spectrum corresponds to the metal and not to the oxide. Hemsalech[3] agrees with Arons, and he has shown that by introducing inductance the line spectrum of the spark between aluminium terminals in nitrogen changes into this same banded spectrum. Berndt[4] concludes from his experiments that the presence of oxygen is necessary for the production of the bands. Lockyer also attributes the bands to the oxide, Wüllner to the metal, Kayser to the oxide, etc.[5] Simple experiments of the author in hydrogen and oxygen in closed tubes have shown that the band spectrum, which is present in considerable strength when the discharge is first sent through the tube, decreases rapidly and disappears in a short time in hydrogen, to appear again after the tube has been allowed to recover for a time. The simplest apparent explanation is that the oxide coating of the aluminium terminals reacts with the hydrogen under the influence of the spark with the formation of water vapor, probably until equilibrium between metallic aluminium, aluminium oxide, hydrogen, and water vapor is reached. On standing the oxide is re-formed and the equilibrium at the lower temperature re-established.

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[1] *Kon. Svensk. Akad.*, 24. [2] *Annalen der Physik*, 1, 700, 1900.

[3] *Ibid.*, **2**, 331, 1900. [4] *Ibid.*, 4, 788, 1901. [5] See references, HEMSALECH, *loc cit.*

The tendency, already spoken of under barium, toward a composite of arc and spark spectra is very evident in the case of aluminium. Not only are the bands and lines of the arc spectrum present, but also several lines which do not belong to it.[1] Most of the lines of the spark spectrum are present in the Wehnelt, some of them with changed intensities. The general appearance is as though a rather weak spark spectrum had been superimposed over a stronger arc spectrum.

It is the intention of the author to return to this and other band spectra of the Wehnelt in a later paper. The intensity of the light from an aluminium point in hydrochloric acid is sufficient to permit of a photograph with a grating of higher dispersion without an excessively long exposure. The spectrum being free from the overlapping carbon bands of the arc, the long band in the violet, which was not examined by Hasselberg, should be very easy of access.

SILVER.

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3281.0......	60	50	30	3982.0......	..	3	..
3330.0......	..	..	2	4055.5......	1	15	5
3358.0......	..	..	2	4212.0......	1	10	10
3383.0......	60	50	50	4228.5......	..	..	1
3540.5......	..	2	1	4312.0......	1	..	1
3583.0......	..	2	2	4476.0......	1	12	8
3630.5......	..	..	1	4668.5......	..	15	10
3682.0......	1	15	1	4875.0......	1	..	1
3781.0......	..	..	1	5209.0.....	100	50	40
3811.0......	..	..	1	5462.0......	20	..	..
3862.0.....	4	..	..	5465.0......	..	50	100
3907.5......	..	1	1	5471.5......	..	20	..
3943.0......	1	1	..	5709.0......	10	..	..
3963.0......	..	..	2				

Spark — Silver electrodes.
Arc — Metallic silver on carbon electrodes.
Wehnelt — Silver wire in hydrochloric acid.

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[1] See KAYSER and RUNGE, *Wied. Ann.*, 48, 120.

With silver as active electrode striking differences of intensity from those obtained in the spark and arc are the rule. Only a few lines come out strongly enough to be reproduced, and the spectrum is in general more like that of the arc than that of the spark. This is shown by the lines at λ 4055.5, λ 4212.0, λ 4476.0, λ 4668.0, λ 5465.0. A number of lines which are strong in the arc are not visible, as, *e. g.*, λ 5471.0, and others are much weaker, like λ 3682.0.

Traces of what appears to be an underlying band spectrum are visible, but the maxima are of such small intensity that a very long exposure would be required to bring out the structure clearly. Such maxima as could be distinctly seen have been placed in the Wehnelt column of the table of wave-lengths.

ZINC.

(Plate XVIII, Fig. 1.)

Wave-Length	Spark	Arc	Wehnelt	Wave Length	Spark	Arc	Wehnelt
3282.5......	20	20	10	4680.5	30	40	40
3302.5......	30	30	15	4722.5	40	50	50
3345.5......	40	50	20	4811.5	50	60	60
3683.5......	..	30	8	4911.5	30	..	8
4058.0......	..	25	5	4924.0	40	..	5
4630.0......	..	10	3				

Spark — Zinc electrodes.
Arc — Metallic zinc on carbon electrodes.
Wehnelt — Zinc wire in hydrochloric acid.

Besides the above lines there are present in the spectrum of the Wehnelt the lines of an underlying band spectrum with heads at approximately λ 3848.0, λ 4238.0, λ 4257.0, λ 4299.0, 4325.0. The finer detail of these bands, from photographs in the third spectrum, will be given in a later paper. The heads of the flutings of the strongest and longest band have wave-lengths as follows:

4163.2
4170.1
4176.5
4182.4
4187.6
4193.7
4199.6
4203.9
4208.0
4212.9
4216.1
4220.2
4226.7
4232.2
4237.8
4242.4
4247.8
4252.5
4256.9 Head

The spectrum of a zinc point used as active electrode offers many interesting differences from the spark and arc spectra of the metal.

1. The triplets λ 3282.5, λ 3302.5, λ 3345.5, and λ 4680.0, λ 4722.0, λ 4811.0, are present with about the same relative intensities as in spark and arc. The lines λ 3683.0, λ 4059.0, λ 4630.0, which are strong in the arc and absent from the spark, are present in the Wehnelt spectrum with lower intensities, but have about the same ratio of intensity as in the arc. The lines λ 4911.0 and λ 4924.0, strong *spark* lines which are absent from the arc spectrum, are present in the Wehnelt, but with less intensity, and are not decreased proportionately.

2. These two lines, λ 4911.0 and λ 4924.0 belong to a class which will be referred to again under tin and lead, broad and diffuse, and distinctly different from the other lines of the spark in appearance. The position of these lines in Kayser and Runge's series[1] has not been determined, and the question as to whether they belong to the same class as the tin lines noticed by Crew[2] is still an open one.

3. The marked underlying band spectrum. This is so faint as to be difficult of reproduction, though a large part of it may be measured, especially the brighter band from λ 4163.0 to λ 4257.0. Here nineteen maxima are visible, but it is in many cases difficult to decide whether lines or the heads of flutings are being measured. These bands seem to be characteristic of this method of producing a zinc spectrum, and the author knows of no other notices or measurements of them.

MERCURY.

The Wehnelt seems to lie about half-way between the arc and the spark in relation of intensity of lines. λ 3278.0 is plainly visible, though of lowest order of intensity in the spark and invisible in the arc spectrum The lines at λ 3650.0, 3655.0, and λ 3663.0 have about the same intensities as in the spark. λ 3984.0 is very feeble, of intensity 4 in the table, as against 40 for the next line, λ 4046.0, and 6 for λ 4078.0. The arc line at

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[1] See *Wied. Ann.*, 43, 395, 1894.

[2] ASTROPHYSICAL JOURNAL, **12**, 167, 1900.

PLATE XVIII.

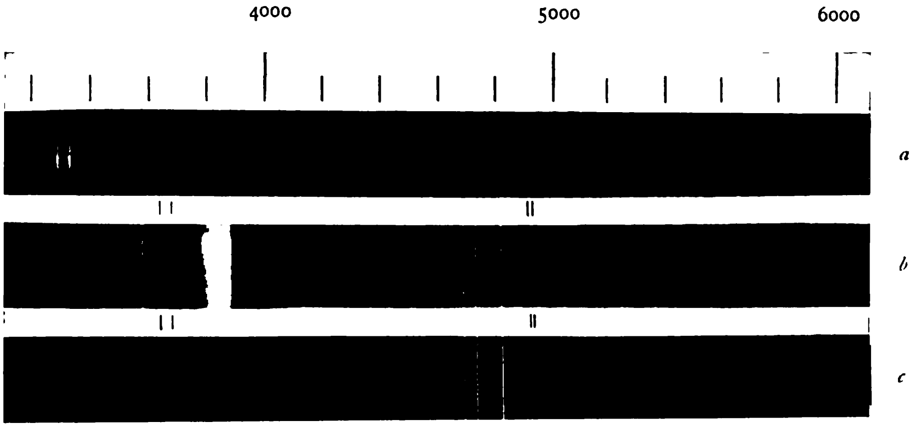

FIG. 1.—(*a*) Spark between zinc terminals.
(*b*) Arc. Metallic zinc on carbon electrodes.
(*c*) Zinc wire in hydrochloric acid.

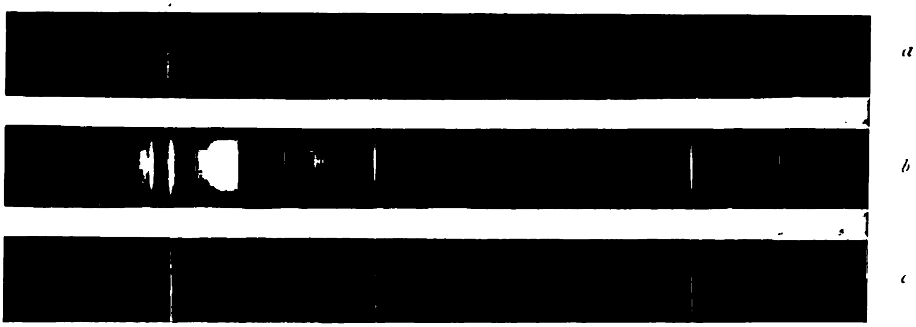

FIG. 2.—(*a*) Spark between amalgamated copper electrodes.
(*b*) Arc. Metallic mercury on carbon electrodes.
(*c*) Platinum point in mercuric chloride solution.

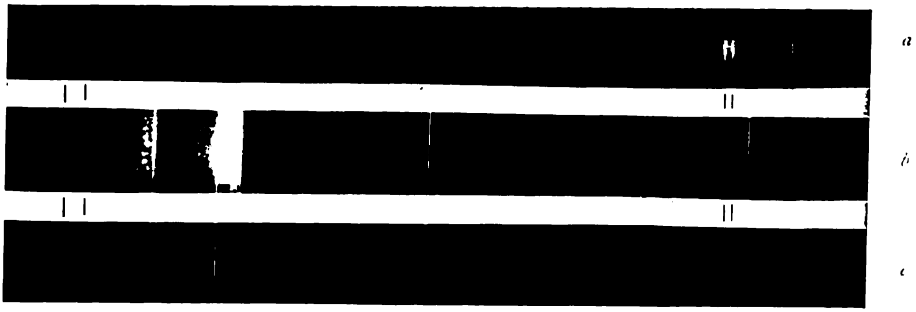

FIG. 3.—(*a*) Spark between tin electrodes.
(*b*) Arc. Metallic tin on carbon electrodes.
(*c*) Tin wire in hydrochloric acid.

MERCURY.

(Plate XVIII, Fig. 2.)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3278.0......	1	..	3	4348.0......	..	7	3
3342.0......	7	20	..	4359.0......	30	40	40
3381.0......	..	..	10	4916.5......	..	5	2
3543.5......	1	6	..	5217.0......	2	..	..
3650.5......	50	15	50	5426.0......	10	..	..
3655.0......	5	10	8	5461.0......	50	100	50
3663.0......	7	15	10	5595.0......	3	..	..
3681.0......	..	8	..	5678.0......	20	..	..
3984.0......	40	5	4	5769.0......	20	50	20
4047.0......	30	20	40	5790.0......	20	50	20
4078.0......	2	15	6				

Spark — Amalgamated copper terminals.
Arc — Metallic mercury on carbon electrodes.
Wehnelt — Platinum point in solution of mercuric nitrate.

λ 4916.5 is plainly visible, while the line at λ 3681.0, also belonging to the arc spectrum, is not to be seen. The spark lines at λ 5426.0 and λ 5678.0 are not present. There is a strong line at λ 3381.0 in the spectrum of the Wehnelt which has not been placed satisfactorily to the credit of any impurity. No traces of a banded spectrum are to be seen.

TIN.

The points of especial interest in the following table are:

1. Marked differences in intensities in spark, arc, and Wehnelt spectra. λ 3283.5 and λ 5332.0 are much weaker in the last than in the spark, and λ 3330.0, λ 3655.5, λ 3801.0, λ 4525.5, λ 5632.0 are much stronger. The spectrum of the Wehnelt is in many parts more like that of the arc.

2. The presence of an underlying band spectrum, containing many flutings, and not present either in the spark or the arc spectrum of the metal. The wave-lengths of these maxima have been placed in the table, without certainty as to whether the maximum in question is a sharp line or the head of a fluting. So far as the author knows, this spectrum of tin has not been observed under any other circumstances.

3. The *appearance* of certain lines. Of striking interest in

TIN.

(Plate XVIII, Fig. 3.)

Wave-Length	Spark	Arc	Wehnelt		Wave-Length	Spark	Arc	Wehnelt	
3175.0	2	3	2		3821.5	..	..	1	Heads?
3249.0	..	..	4		3837.5	..	..	2	
3262.5	15	10	20		4046.5	..	..	1	
3273.5	..	..	3		4307.5	..	..	1	
3283.5	20	..	3		4382.5	..	..	2	
3330.5	3	10	30		4512.0	..	..	1	
3352.0	30	..	8		4525.5	8	40	100	
3392.0	..	..	1	Heads of flutings?	4586.0	10	..	1	
3416.5	..	..	1		4617.3	..	..	2	Heads?
3446.5	..	..	1		4651.5	..	..	1	
3472.5	..	..	1		4722.0	..	..	1	
3487.3	..	..	4		4810.0	..	..	1	
3571.5	..	..	1		4858.0	10	..	5	
3589.0	..	..	4		4923.0	2	..	..	
3619.0	..	..	1		5100.5	8	..	2	
3639.0	..	..	8		5147.5	..	..	1	
3655.5	1	8	10		5223.0	4	..	..	
3693.2	..	..	1	Heads?	5243.5	..	..	1	
3723.4	..	..	2		5290.0	2	..	..	
3734.9	..	..	2		5332.0	50	..	7	
3746.0	1	..	1		5562.0	100	..	20	
3801.0	15	30	80		5588.0	100	..	15	
					5632.0	..	10	10	
					5798.0	50	..	10	

Spark — Tin electrodes.
Arc — Metallic tin on carbon electrodes.
Wehnelt — Tin wire in hydrochloric acid.

this connection is the pair of lines at λ5562.0 and λ5588.0. These lines are strong in the spark, absent from the arc, and of small intensity in the Wehnelt spectrum as compared with the spark. They are also the most striking lines in the spark spectrum on account of their marked breadth and diffuseness. The lines at λ3283.5 and λ3352.0 have the same peculiarities in a much less degree, and they also follow the same course in their varying intensities in the three spectra.

A similar change in the latter pair of lines has been observed in the arc between tin electrodes in an atmosphere of nitrogen, these lines being much weaker than in the spark in air.[1] In ammonia gas and hydrogen they are greatly *enhanced*. The possibility of the formation of metal-hydrogen compounds in the

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[1] See PORTER, ASTROPHYSICAL JOURNAL, 15, 274, 1902.

Wehnelt and of a similar influence of the atmosphere of mixed hydrogen and oxygen is suggested, though other cases (see aluminium and magnesium) seem to indicate the preponderance of the action of the oxygen freed by the dissociation of the water vapor.

Some evidence in the matter is given by the research of Crew[1] on the arc spectra of metals in hydrogen. The results which seem to have bearing in this case are:

1. "All lines in the arc spectrum which are affected by hydrogen, whether enhanced or diminished, belong to the spark spectrum also.

2. "Lines which belong to Kayser and Runge's series are unaffected by the change from air to hydrogen."

These conclusions cannot be applied as a whole to the spectra of the Wehnelt, but something very similar to the second of them seems to be true for zinc, tin, and lead (see lead).

LEAD.

(Plate XVI, Fig. 6.)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3573.0......	20	20	25	4245.0......	100	..	6
3640.0......	20	25	40	4387.0......	100	..	5
3671.5......	10	20	8	4478.0......	..	10	..
3683.5......	50	20	30	5005.5......	6	..	3
3726.0......	..	20	..	5045.0......	8	..	..
3740.0......	30	..	25	5201.5......	..	5	..
3854.0......	15	..	..	5372.5......	10	..	1
4019.5......	10	20	8	5546.0......	10	..	1
4058.0......	100	40	50	5588.0......	..	3	..
4062.5......	10	8	6	5607.0......	10	..	..
4168.0......	10	12	5	6002.0......	..	4	..
4242.0......	10	..	..	6020.0......	..	..	10

Spark — Lead electrodes.
Arc — Metallic lead on carbon electrodes.
Wehnelt — Lead wire in hydrochloric acid.

The absence of several of the strong lines of the spark spectrum is of interest (λ3854.0, λ4242.0, etc.). The strong pair of spark lines at λ4245.0 and λ4387.0, which is entirely absent from the arc spectrum, is present in the Wehnelt, but with greatly diminished intensity. This pair is one like those already referred to under zinc and tin, differing from the other lines of the spark spectrum in appearance by being broader and more diffuse.

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[1] *Ibid.*, **12**, 167, 1900.

The spectrum of a carbon point in various acids has also been photographed. None of the plates shows any lines or bands which are not directly traceable to impurities in the carbons used. About ninety lines of iron, twelve of calcium, and two of aluminium were measured in one case. These lines were superimposed on a continuous spectrum of considerable intensity, but no bands were observed. (See Plate XVI, Fig. 1.)

Preliminary tests on salts containing complex ions have given results of interest. A carbon or platinum point in a solution of potassium ferrocyanide gives lines of potassium and iron and no new lines. Potassium chromate as electrolyte absorbs all but a small strip of actinic light, but of a dozen lines measured in the vicinity of the D lines, two were lines of potassium and the rest were lines of chromium, the triplet $\lambda 5204 - \lambda 5208$ being strong.

Besides the metals described, the following have been photographed in the Wehnelt, both in the first and third spectrum: copper, nickel, iron, gold, palladium, platinum. Data on the measurements of these spectra will be given in a later paper.

As has already been stated, no effect of the anion has been observed at any time. The breaking up of the chromate ion and the appearance of the lines of metallic chromium in the case of potassium chromate, and the fact that all the salts of the same metal gave identical spectra, show this clearly. The facts all point to the high temperature as the cause of the luminescence, and to the probability that the electrolysis plays a purely secondary part.

Although no effect of the anion is observed, the spectra produced by this arrangement are in many cases compound spectra, if we are to accept the sharp distinction of *compound* and *metallic* or elementary spectra, as evidenced by the presence or absence of *bands*. Aluminium, magnesium, calcium, barium, give the bands which are ascribed to their oxides, and zinc and tin give fluted spectra which appear to be of the same general type. The presence of free oxygen and hydrogen at a temperature above the point of dissociation of water affords the possibility of a a strong oxidizing action on any metal, and the opportunity for the exhibition of an oxide spectrum when the dissociation temperature of the oxide in question lies at a point higher than the dissociation temperature of water. That the free hydrogen in the mixture of gases could, under these conditions, form metal-hydrogen compounds[1] seems more than doubtful; yet the variations between Wehnelt and spark and arc in air bear a striking resemblance to the variations in the arc spectra of the same metals in air and hydrogen, and in the latter case the necessity for the assumption of such metal-hydrogen compounds seems to be felt.[2]

Although the spectra under discussion are in many ways similar to those produced by allowing the spark to pass from a metallic point to a solution of a salt, many of the characteristic bands of compounds produced by the latter method are absent in the Wehnelt. Compound spectra, varying from salt to salt, are the rule in the more volatile metals[3] when the spark passes to a solution of one of their salts. The point used gives, in the Wehnelt, all the strong lines of the metal, even of platinum, while in the other method the lines of the electrode are but faint.

The tables and plates show the following general points of especial interest:

1. The lines of the Wehnelt spectra include some which have been usually ascribed to the spark and some which have been ascribed to the arc; usually the spectrum is closely allied to that produced in the spark, but often *some of the strongest lines are missing*. Other researches which give evidence as to the effect of varying conditions on spectrum lines serve to strengthen the conclusion which must be drawn—that there is no sharp boundary between arc and spark, and that the transition from "arc" spectrum to "spark" spectrum is a gradual and continuous one.

2. Under constant conditions a spectrum may contain the

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[1] See LIVEING and DEWAR, *loc. cit.*

[2] See BASQUIN, *loc. cit.*, and PORTER, *loc. cit.*

[3] LECOQ, *Spectres Lum.* atlas.

strongest lines of the condensed spark and at the same time lines usually ascribed to the flame.[1]

3. Under the same conditions the "oxide bands" may be present at the same time as the strong spark lines.[1]

4. Under the same conditions the spectrum of zinc contains, besides lines belonging to both spark and arc spectra, a band spectrum not hitherto observed under any conditions. The same is true of the spectrum of tin in the Wehnelt interrupter.

5. Certain lines which are of broad, diffuse appearance in the spark and are absent from the arc spectrum of the metal, are present in the Wehnelt spectrum, but much decreased in intensity. The metals which show this phenomenon most sharply are zinc, tin, and lead.

The first thought is, of course, that we are dealing with a complicated process, involving an entire series of temperatures from that sufficient to give the band spectrum of a compound to that necessary to produce the strongest lines of a difficultly fusible metal like platinum or chromium, and that the point and the space about it pass through this series of temperatures at each interruption of the current. The result would be a spectrum which was the sum of the spectra corresponding to the various temperatures through which the system passes. Such a conclusion should be evidenced by the presence of all the lines of all the spectra, and if we are to couple each spectrum with a definite temperature, we should expect the resulting composite to be complete. But in none of the cases examined are all of the lines of the various spectra present. Some strong lines are, and some are not, present in normal intensity. So this conclusion, though perhaps the simplest consistent with our present knowledge of temperature and spectra, and the relation between them, seems not to explain the facts.

The interrupting action in the Wehnelt is undoubtedly caused by the intense heating due to the high current density about the small point. The heat vaporizes and then dissociates the water into hydrogen and oxygen, as has been shown by the analyses of Voller and Walter (*loc. cit.*) and others. That spectra like those of the oxy-hydrogen flame should result from the explosion of the mixed gases by the hot metal in the cooler parts of the gaseous envelope is not surprising; it is rather remarkable that not more of the characteristic flame spectra were observed. At the same time, the great affinity for oxygen of such metals as aluminium, magnesium, calcium, and barium might explain the appearance of the bands belonging to the oxides of these metals.

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[1] See on these points LIVEING and DEWAR, *loc. cit.;* also *Proc. R. S.*, **32**, 189, 1881.

The one point which is difficult of explanation by any reasoning based on the assumption of a varying temperature is the absence of some of the characteristic strong lines, while others usually ascribed to the same temperature are present.

It seems probable that the environment of the point does pass through a very great range of temperature with each interruption of the current. There seems to be no reason for believing that the same is not true of the spark in air and the arc. In the spark in air the discontinuity of succeeding oscillations is quite complete, and the necessity for an explanation of the absence of lines ascribed to the lower temperatures seems as evident as in the case at hand. It seems probable that all three of these spectra, spark, arc, and Wehnelt, are composites, though this is not so evident in the usual methods of spectrum production.

In the Wehnelt, reversals were not observed in any case. This is remarkable, since Hale,[1] Hale and Kent,[2] Lockyer,[3] and others who have examined the spectra of the arc under liquids have shown that a very strong tendency toward reversal may exist under these circumstances. The mechanism of spectrum production in the two cases must be very different.

Lockyer gives, as the result of his investigations and as the basis of many deductions, four distinct stages of temperature, corresponding to the spectra of metals as they are produced in the laboratory. They are:

1. "The flame spectrum, consisting of a few lines and flutings

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[1] ASTROPHYSICAL JOURNAL, 15, 190, 1902.

[2] *Ibid.*, 17, 155, 1903.

[3] *Ibid.*, 15, 190, 1902.

only, including several well-marked lines, some of them arranged in triplets.

2. "The arc spectrum, consisting of many lines.

3. "The spark spectrum, differing from the arc spectrum in the enhancement of some of the short lines and the reduced relative brightness of others.

4. "A spectrum consisting of a relatively very small number of lines which are enhanced in the spark. This latter spectrum is produced at a temperature which is that of the very center of the spark."

Lockyer has also made frequent use in his writings of a diagram showing a series of furnaces of increasing temperature, spectra being used to designate the temperature in each. The flame is taken as the lowest, the arc next, and then the spark, followed in application to astrophysical comparisons by the spectrum of a typical cooler star, than hotter ones, and so on. We have in the Wehnelt interrupter a "furnace" in which under constant experimental conditions a banded (compound) spectrum like that found for aluminium, and a pure line spectrum like that found for platinum, may be produced. The amount of current passing in the two cases is the same, the other factors of the experiment (composition of electrolyte, size of electrodes, etc.) remain constant, and there is every reason to believe that the maximum temperature reached is the same in the two cases. Any criterion of the temperature corresponding to either of these spectra would appear to be wanting unless they correspond to the *same* temperature. Nor does the fact of the absence of some of the strong lines of a metal appear to offer any measure, however qualitative, of the temperature, since other strong lines usually belonging to the same temperature are present.

It is certainly very easy to be led into reasoning in a circle in a case where much of our knowledge of temperatures has been deduced from observations on spectra, and much of our theory as to the correspondence of certain spectra with certain temperatures has been drawn ultimately from the same source.

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THE SPECTRUM OF THE AURORA.

By E. C. C. BALY.

IN the December number of the ASTROPHYSICAL JOURNAL[1] Professor Runge has drawn attention to Professor Paulsen's paper[2] upon the spectrum of the aurora, in which a comparison was drawn between this and the negative glow spectrum of a vacuum tube containing oxygen, a little nitrogen, and carbon monoxide. Professor Runge quite rightly, I think, points out that this comparison is misleading, as more striking results are obtained if we compare together the spectra of krypton and the aurora. In support of his contention Professor Runge gives a table of wave-lengths of the aurora lines together with some krypton lines, and also Paulsen's vacuum-tube lines; and he says that before any definite conclusions can be drawn more accurate measurements of the aurora lines are required. Recently Sykora[3] has published some measurements of these lines made from photographs taken at Spitzbergen in the winter of the year 1899. The figures he obtained are probably at least as accurate as any hitherto published, and a comparison of these with the krypton spectra gives an even more striking result than Professor Runge shows in his paper. In the table given below, lines are taken from both the krypton spectra; this is, I think, perfectly justifiable, for the following reason: Without doubt the auroral discharge takes place through very rarefied gas, especially if the atmospheric krypton be the main carrier of the electricity. It has long been known that when the ordinary discharge is passed through argon under reduced pressures, the red spectrum only is visible, unless the pressure be too low, when the blue spectrum and the red spectrum are simultaneously seen. The same is true of krypton, for when the pressure is greater than a certain small value, only the first krypton spectrum is visible; if now the pressure be reduced, a stage is soon reached at which the second, or jar and spark-gap spectrum makes its appearance, so that the two spectra are seen together. Such a condition might perfectly well obtain in the case of the aurora, and therefore lines are taken from both spectra in the following table.

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[1] ASTROPHYSICAL JOURNAL, 18, 381, 1903.

[2] *Rapports présentés au congrès international de physique*, 3, 438. Paris, 1900.

[3] *Acad. Sci. St. Pétersbourg, Mém.*, XI, 9, 1, 1902.

AURORA		KRYPTON	
λ (Sykora)	Character	λ (Baly)	Intensity
5570	Strong	5570.50 (*ab*)	10
4710	Weak	4710.68 (*b*)	1
4429	Very weak	4431.85 (*b*)	4
4354	Very weak	4355.67 (*b*)	10
4276	Very strong	4274.15 (*ab*)	10
4190	Very weak	4185.29 (*b*)	2
4083	Very weak	4082.58 (*b*)	4
4057	Weak	4057.17 (*b*)	8
3995	Weak	3994.98 (*b*)	6
3912	Strong	3913.01 (*b*)	1
		3912.69 (*b*)	5
3804	Weak	3804.80 (*b*)	4
3754	Weak	3754.35 (*b*)	5
3707	Very weak	3708.23 (*b*)	1

The above measurements of the krypton lines are my own,[1] and the letters after the figures refer to the spectrum; *ab* means that the line is common to the two krypton spectra, and *b* that the line is only to be found in the second, or jar and spark-gap spectrum.

In addition to the above lines, Sykora says that there are many others which were too faint to measure. Paulsen gives in his list some other lines, not included in the above table, and these may be quoted here, as there are krypton lines sufficiently near to justify a comparison.

The last two bands or groups of lines clearly include the lines given by Sykora.

It may be pointed out that some of the krypton lines given above are among the weakest in the spectra of this gas; this is, however, no objection, as under certain conditions, when krypton is very much diluted by admixture of other gases, it is the

[1] *Phil. Trans.*, A, **202**, 183, 1903.

Aurora		Krypton	
λ in $\mu\mu$ (Paulsen)	Intensity	λ (Baly)	Intensity
463	10	4634.05 (*b*)	5
455	10	4556.77 (*b*)	4
449	10	4490.04 (*b*)	4
441.5–439.0	1	4408.10 (*b*)	2
		4386.69 (*b*)	4
436.0–430.5	1	4355.67 (*b*)	10
		4301.71 (*b*)	3
		4300.67 (*b*)	3
		4283.17 (*ab*)	4
428.5–425	10	4274.15 (*ab*)	10
		4268.97 (*b*)	3
		4268.72 (*b*)	2
		4259.60 (*b*)	3
		4254.98 (*b*)	3

weakest lines that are visible first. For example, in the spectrum of atmospheric argon only three of the krypton lines are visible, and these are some of the weakest in the krypton spectrum. Indeed, the line given in the second table at $\lambda = 4408.10$ is one of these, and this fact may even be taken as an argument in favor of its appearance in the aurora.

There hardly seems any doubt, from the above figures, of the very close connection between the auroral spectrum and the krypton spectra; further, it seems that it is the second krypton spectrum that is most concerned. This fact is, as stated above, only to be expected, if we consider the probably rarefied condition of this gas at the high altitudes at which the discharge takes place.

Spectroscopic Laboratory,
University College, London,
January 1904.

ON THE ANALYSIS OF BRIGHT SPECTRUM LINES.

By JAMES BARNES.

IT is well known that a change is produced in the wave-length and distribution of light in the lines of the spectrum of metallic vapors and gases when different external conditions are introduced. In most cases these changes were first observed and measured by means of the Rowland grating. Recently, however, these effects have become more readily observable through interference methods, in which the interference bands are produced with large differences in the paths of the rays.

Michelson,[1] by aid of his interferometer, resolved the important lines in the radiations of some vapors and gases rendered luminous in vacuum tubes, and he has studied these radiations in a magnetic field. With his echelon spectroscope he has investigated the same subjects. Fabry and Perot[2] with their interferometer have investigated the radiations from vapors in the electric arc and in vacuum tubes, and have applied their method for an exact determination of the wave-length of some of the lines in the spectrum of the iron arc and of the dark lines in the Sun's spectrum. Lummer[3] also by an interference method has studied the same radiations, particularly those from mercury, and has separated its prominent lines into many components.

When one compares the results of these investigations, the agreement is not very satisfactory. Not only do the number and intensity of the components differ, but the distances between the components do not agree.

The work presented in this paper was undertaken at the suggestion of Professor Ames. The objects of the work were: to study interferometer methods; to obtain, if possible, more consistent results as to the constitution of the lines; and to determine the changes produced in the components under various conditions. Michelson remarks, in one of the papers cited:

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[1] *Phil. Mag.*, (5) **31**, 338, 1891; **34**, 280, 1892.

[2] *Ann. de Chim. et Phys.*, **12**, 459, 1897; **16**, 115 and 289, 1899. ASTROPHYSICAL JOURNAL, **9**, 87, 1899.

[3] *Verhandlungen d. D. Phys. Ges.*, **3**, 85, 1901. *Physikalische Zeitschrift*, (3) **8**, 172, 1902.

> Still, in many cases, the range of visibility due to slight variations in the conditions shows that the behavior of each substance must be carefully studied under all possible circumstances of temperature, pressure, strength of current, size and shape of electrodes, diameter of vacuum tube, etc.

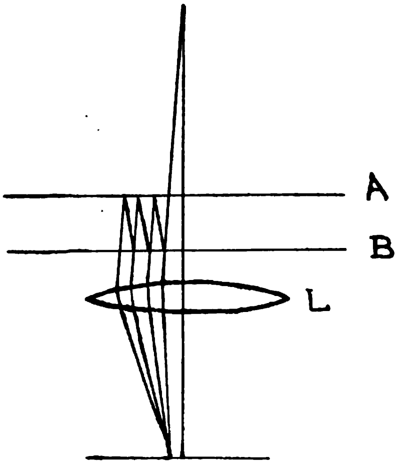

FIG. 1.

After experimenting a few months with both the Michelson and the Fabry and Perot interferometer, the author was fully convinced that the Fabry and Perot method possessed the advantage for the problems in view, since it shows directly the structure of a given radiation by the simple inspection of the system of fringes. Each fringe is, in fact, a true spectrum of the source, and the conditions are the same as those existing in the spectra obtained by the use of a grating having a small number of lines, but where the spectra employed are of a very high order. During the progress of the experiments the method proposed by Lummer appeared. While I have not been able to use this method exactly, I used, before I read his paper, one which is very similar to it. This method and results obtained will be described below.

METHOD.

The method involved in this production of interference fringes will be first briefly considered, as it will assist toward a clear conception of the results.

Consider a ray of monochromatic light incident at an angle θ upon two glass plates, whose inside surfaces A and B (Fig. 1) are slightly silvered and separated from one another by a distance D. If the silvered surfaces are parallel, we have, on account of the multiple reflections, a number of transmitted rays coming from the same source, whose differences of path increase in arithmetical progression. The differences of path with respect to the first are $2D\cos\theta$, $4D\cos\theta$ . . . . . $2nD\cos\theta$. By means of a lens L these rays are brought to a focus in its focal plane, producing there an interference pattern, bright and dark bands, according as $2D\cos\theta$, $4D\cos\theta$, etc., are equal to an even or an odd number of half wave-lengths. If we have a symmetrical cone of rays incident upon the plates, the system of fringes obtained on a screen placed in the focal plane of the lens will be concentric circles, having as their center the point of intersection of the normal from the source upon the plates with the screen, C in the figure. The radii of these circles are equal to $f\tan\theta$, where f is the focal length of the lens L.

The intensity of the light at different points in this interference pattern was first worked out by Airy.[1] His formula is:

$$I=\frac{I_0(1-b^2)^2}{(1-b^2)^2+4b^2\sin^2\left(\frac{\pi\Delta}{\lambda}\right)},$$

where I_0 is the intensity of the incident light transmitted by the silvered surfaces, b the coefficient of reflection of the silvered surfaces, and Δ the difference of path of the rays. We see from this formula that for a given value of b, I will have a maximum when $\frac{2\Delta}{\lambda}$ is an even integer and a minimum when $\frac{2\Delta}{\lambda}$ is an odd integer. Hence the intensity of the bright fringes is I_0, while that of the dark fringes is

$$I\left(\frac{1-b^2}{1+b^2}\right)^2.$$

Fabry and Perot have calculated the values of I for different values of b, and have plotted curves showing the relation between I and Δ for these values of b. The greater the value of b, the steeper becomes the intensity curve, so that the interference pattern consists of bright fringes which are very narrow compared with the dark ones (see Plate XIX, Fig. 1). As we shall see later, the sharper and finer these bright bands are, the easier are the radiations analyzed and the components measured. Thus, while on this account it is advantageous to have b very large, by increasing the thickness of the silver film, it must not be so large that I_0. the intensity of the light transmitted, is too small.

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[1] *Phil. Mag.*, (3) 2, 20, 1833.

Let us now consider the light which is incident upon the plates not to be monochromatic, but to consist of two wave-lengths λ and $\lambda + d\lambda$; then the screen in the focal plane will be covered with two systems of concentric rings. At a definite separation of the plates let these two systems be in coincidence, then we have the relation

$$\frac{\Delta}{\lambda} = \frac{\Delta}{\lambda + d\lambda} + n \; ,$$

where n is any whole number, or

$$d\lambda = \frac{n\lambda^2}{\Delta - n\lambda} \, .$$

Since Δ is always large relative to $n\lambda$, we may write

$$d\lambda = \frac{n\lambda^2}{\Delta} = \frac{n\lambda^2}{2D\cos\theta} \, .$$

Thus by observing the first coincidence of the rings ($n = 1$) near the center of the system, where θ is so small that we may consider $\cos\theta = 1$, knowing the value of λ, and measuring D, the value of $d\lambda$ can be determined with a very high degree of accuracy. When $d\lambda$ is very small, it is not necessary for the determination of its value to separate the plates until the first coincidence occurs, but only till the separation of the rings is clearly visible. When the separation of the systems of rings is, say, one-quarter of the distance between consecutive rings of the same radiation, the equation becomes

$$d\lambda = \frac{\lambda^2}{8D} \, .$$

The resolving power of this method depends upon the distance between the plates, and also upon the angle of incidence of the light. The fringes near the center have thus the largest resolving power. It is also advantageous to make observations upon the central fringes, because their separation is the greatest.

This can be shown if we consider the length of the radii of the rings. With the center of the system a bright ring,

$$\Delta = 2D = m\lambda ,$$

where m is an integer; for the first bright fringe out from the center, the difference of path is

$$2D\cos\theta = (m-1)\lambda ;$$

hence,

$$\tan\theta = \frac{\sqrt{2m-1}}{m-1} ,$$

and the radius R_1 of the ring is given by the expression

$$R_1 = f\tan\theta = f\frac{\sqrt{2m-1}}{m-1} .$$

Similarly for the second bright fringe

$$2D\cos\theta = (m-2)\lambda ;$$

hence,

$$R_2 = f\frac{\sqrt{4m-4}}{m-2} ,$$

and so forth for R_3, R_4, etc.

The following table gives the values of R_1/f, R_2/f, etc., for different values of m:

m	R_1/f	R_2/f	R_3/f	R_4/f	R_5/f
1	∞				
2	1.732	∞			
3	1.118	2.828	∞		
4	0.882	1.732	3.873	∞	
100	0.143	0.203	0.251	0.292	0.329

From this table we see that when $m = 1$, *i. e.*, the difference of path is one wave-length, there is only one interference band, and its radius is infinite. Thus the field would be uniformly illuminated. When the difference of path is two wave-lengths, there are only two fringes, the first whose radius is 1.732 f, the radius of the second being infinite. For $m = 3$ there are three fringes. The entire system of bands could be observed only by means of infinite glass plates. We also see that as m gets large, which in practice is generally the case, the lower row in the table shows us that the distance between the first and second rings is much larger than that between the second and third, and so on moving out in the system. Thus the separation of the fringes gradually diminishes as we go out from the center, and hence the advantage of making the observations on the central fringes. This is clearly shown by the figures on the plates, which are reproduced from photographs.

This interference method, besides being applied for the analysis of spectrum lines, can be used in the study of the changes in the wave-length of any radiation under the different conditions, as indicated above. Any small change will be shown by an increase or decrease in the diameters of these rings, and since very clear photographs can be taken, very accurate measurements of the changes produced can be obtained.

APPARATUS.

After experimenting some time with an instrument which seemed to be particularly sensitive to vibrations, even when every precaution was taken to eliminate extraneous disturbances, a new instrument was constructed. In the construction of this instrument the essential parts sought after were that the mountings for the plates should be rigid and placed on a massive base, so that the bands should be perfectly steady, and that the movable carriage carrying one plate should be capable of very slow uniform motion, always remaining parallel to its original position, enabling one to follow clearly the change from one band to another.

In working with a Michelson interferometer, as made by Gaertner & Co., the fringes obtained were very steady, even when the instrument rested on a table in the laboratory. I took this instrument, stripped it of its mirrors and plates, and, using the base, carriage, and screw, constructed the apparatus employed.

The apparatus consists of two plane glass plates 3.9cm by 2.5cm and about 0.6cm thick, each slightly prismatic in shape; the two faces making with one another an angle between 1″ and 2″. This prevents the interference bands formed in the plates themselves being superimposed upon those under observation. Both plates are rigidly mounted in brass frames. One frame can be moved about a vertical axis and the other about a horizontal axis. For very small motions about these axes, so that the silvered surfaces may be made perfectly parallel, two glass tubes were bent into convenient shapes and clamped to the instrument. Their ends, resting against the frames, are covered with thin sheet rubber. To the other ends are attached long rubber tubes, and these are connected with a support. By carefully raising or lowering these tubes, which are filled with mercury, the pressure against the frames being therefore varied, very small rotations around either axis are obtained, and the surfaces thereby placed in perfect adjustment. Fabry and Perot employed this method, using water in their tubes instead of mercury. The carriage containing one of the frames rests upon steel ways, very accurately ground, and is connected by means of a small çarriage, placed underneath, to a screw of 1 mm pitch. The force, being thus applied to the carriage in a direction parallel to the motion, produces no rocking, as is shown by the fact that the fringes always remained in adjustment during the motion.

To turn the screw, two handles are on the instrument, one for rapid and the other for slow motion. A turn of the first corresponds to one turn of the screw. The other is a tangent screw by which it is possible to give the carriage such a slow motion that the change from one fringe to the next can be easily followed. To both handles were attached graduated disks, enabling the distance between the plates to be accurately known.

The whole instrument weighed over 15 kg and was placed on a brick pier. The greater part of the observations were taken at night. With this instrument the fringes were always perfectly steady, and very long photographic exposures could be made without the least fear of obtaining a blurred image.

Since the radiations from all the sources studied consisted of many wave-lengths, it was necessary to employ some arrangement by which the wave-length under consideration could be separated from the others. The following (Fig. 2) was the plan first adopted. *S* is the source of light. The radiation undergoes an analysis by a Steinheil spectroscope consisting of two flint-glass prisms. The lens *L* brings the different wave-lengths to a focus on a screen *I*, which contains a slit. Through this slit the wave-length considered is allowed to pass, and passing between the silvered plates forms the interference bands, which are observed by a telescope *T* or photographed.

The photographic apparatus consisted of a long light-proof box, which had a circular hole cut in one side. The eyepiece of the telescope being removed, the box was placed so that the opening fitted over the end of the telescope. The photographic plate, 13 × 3 cm, was in the focus of the objective and mounted so that it could be slid past the opening, and hence a number of exposures made upon one plate.

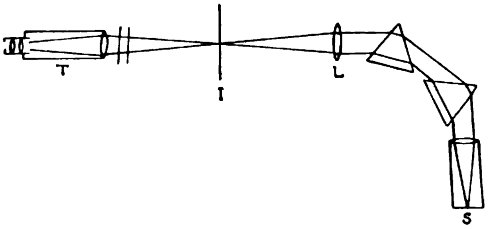


FIG. 2.

With the silvered plates illuminated in this way, with divergent light, the entire rings of the interference bands are observed in the focal plane of the objective as shown on Plate XIX, Fig. 1. The following method, however, was found to be better for the analysis of the radiations. The lens *L* was removed and the interferometer placed directly behind the prisms, so that the parallel light fell upon the silvered plates. With a broad slit in the spectroscope we have in the telescope, focused for infinity, broad lines corresponding to the lines in the spectrum. These lines are crossed with the interference bands produced by the plates. By this means the light has been concentrated into a few interference bands, and on this account many of the weaker components appear which cannot be seen with the light divergent as above. Fig. 2 (Plate XIX) shows this clearly. This photograph is of the bright-green mercury radiation, and shows three components when the interference plates are separated 8 mm.

This method possesses also another great advantage. Due to the number of lines in most spectra, we have in the field of the telescope at the same time a number of lines containing different kinds of interference bands depending upon the constitution of the radiation making up each line. This facilitates greatly the analysis of the radiations, and we see at once any change that may take place in one or all of the lines through any change of external conditions. The dispersion of the prisms and the magnification of the telescope were such that about half of the spectrum was visible at once. In Plate XIX, Figs. 3, 4, and 5 each show the interference bands due to the two yellow and green lines of mercury vapor taken at the same time with the plates separated at different distances. On account of the broad slit, the yellow lines passed through the interference plates together, and hence their interference bands are superimposed upon one another. The other lines in this region of the spectrum of mercury, being of less intensity, do not show in the photographs, which were exposed only long enough to get the clearest pictures of the lines considered. The dark-green line was quite visible to the eye after passing through the silvered plates. The curvature of the bands in the different lines is, of course, due to the amount of separation of the plates and to the angle of incidence with which the radiations are incident upon the interferometer plates.

For the determination of the scale-reading corresponding to the place where the silvered plates were in contact, a sodium flame or incandescent sodium vapor in a vacuum tube was employed. The slit of the spectroscope being wide, the two D lines were superimposed so that the two radiations together entered the interferometer. The plates were separated until the first coincidence happened, and the readings taken; the operation was repeated several times. Since the difference, $d\lambda$, between the sodium lines is known with accuracy from Rowland's tables, the distance D between the plates can be calculated from the above equation, and thus the zero point obtained. Readings were taken of the successive coincidences as the plates were separated, and in this manner the screw was calibrated. If a more accurate calibration is required, the two yellow lines of mercury can be used; since their distance apart is about three times that of the D lines, the coincidences occur three times more often in a given distance.

REMARKS ON INTERFERENCE BANDS.

Before considering the results, I will add some remarks concerning the general character of the interference bands obtained by this interference method.

When the silvered surfaces are not parallel, but are inclined to one another at a small angle, the fringes obtained are localized in the plates, and, as is well known, can be seen by the eye or with a lens focused on the plates. These fringes, however, can be obtained only when the separation of the plates is very small.

In order to procure clear interference bands with great differences of paths, it is necessary to have the surfaces rigidly parallel. The fringes in this case are seen by the eye, or by means of a telescope focused for infinity. One of the most important results of this work is that *the silvered faces of the plates must be perfectly parallel, and the telescope must be focused for infinity, to obtain correct results.* While this has been noted by former investigators, I wish strongly to emphasize the necessity for these adjustments; for if these two conditions are not fulfilled, all manner of anomalous results may be expected.

On Plate XIX are shown some photographs of some of the results obtained, if these conditions are not obeyed. Figs. 6–12 were all taken with the bright green line of incandescent mercury vapor in a vacuum tube. None of the photographs is magnified; the focal length of the objective used was about 15 cm.

The separation of the interference plates in Figs. 1, 6, and 7 was 3 mm. Fig. 1 is where the adjustments are perfect; Figs. 6 and 7 show the effect upon the bands when the interference plates are only a very small degree from being parallel, they being displaced from parallelism by merely raising one of the mercury adjusting tubes less than 1 cm. In Figs. 8 and 9 the plates are separated 0.5 mm, the plates in neither case being parallel. In Fig. 8 they have an angular separation of over 1″. These photographs also show the interference bands produced *in* the plates themselves superimposed upon the other.

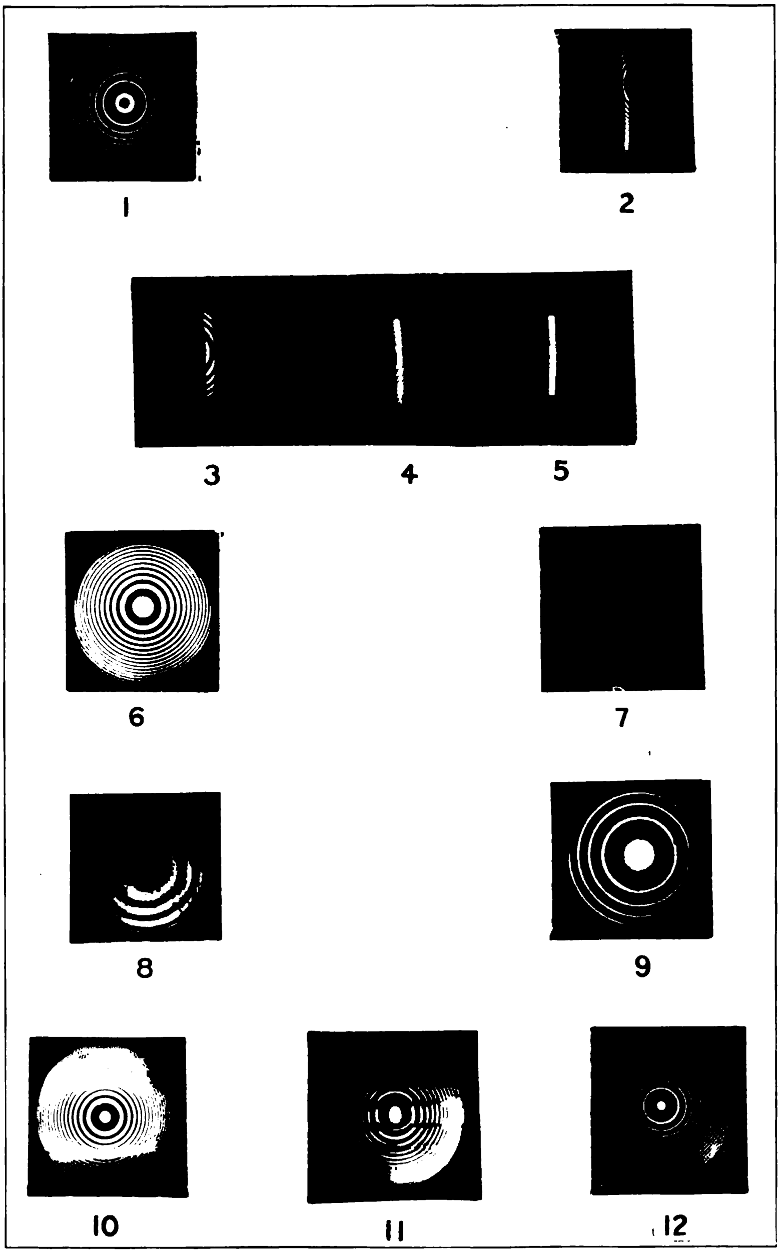
As it is to advantage in the observations to obtain all the light possible, a broad source is always employed. The interfering rays from the different points of the source can produce a clear interference pattern only in the focal plane of the objective; in any other plane the bright interference bands will be wide and hazy. Figs. 10, 11, and 12 illustrate this point. The whole slit is covered, with the exception of two points separated 4 mm from one another in a horizontal direction. Fig. 10 shows the effect when the photographic plate is placed about 1 cm inside the focus of the objective; Fig. 11, when the plate is placed 2 cm beyond the focus; Fig. 12, when the plate is exactly in the focal plane; then the fringes produced by all points of the source are coincident, and give clear and sharp interference fringes. One can easily see that if the whole source were used instead of two points, the bands in Figs. 10 and 11 would be wide and hazy, so that if any of the bands due to the components of the radiation were present, they would probably be entirely obliterated.

To set the telescope at infinity is easy, but the adjustments necessary to obtain the silvered surfaces parallel are more or less difficult, and can be obtained only with practice. The plates are parallel when the fringes are sharp and the illumination equally distributed over the series of rings due to the components.

A REFLECTING INTERFEROMETER.

In the Fabry and Perot interferometer a large amount of light is lost, due to reflection from the surface of the silvering in contact with Plate A, Fig. 1, so that only a small percentage is transmitted. To eliminate this defect the plates were mounted according to the following Fig. 3. Plate A was heavily silvered and polished on its inside surface, and mounted on the carriage of the interferometer as described above. Plate B has its inside surface almost completely silvered, its reflecting power being about 0.9, and is mounted in the other frame. Light is incident upon Plate A, as shown in Fig. 3, and, due to multiple reflections between the silvered plates, we have transmitted a number of rays whose path-differences are in arithmetical progression, and the theory of the method is exactly as that sketched above. By this method the bright interference bands are much brighter than those obtained with the Fabry and Perot method, and hence the components are more readily seen. On account

PLATE XIX.



Interference Fringes under Varied Conditions.

of the larger incident angle θ of the light upon the plates, the fringes observed are quite a distance from the center of the system, and are therefore close together, causing the necessary adjustments to make the plates parallel more difficult than with the method above, where the center of the system is used. Observations were made with these two methods, and the results agreed extremely well.

As mentioned in the introduction, a method proposed by Lummer appeared during these experiments. He employs only a long glass plate with parallel faces, and passes light into it by means of a prism at such an angle that it emerges at almost the critical angle. The method is very similar to the method above. In Lummer's method, however, since the thickness of a given glass plate is fixed, the positions of the components relative to one another cannot be determined; and if the faces of the plates are not perfectly parallel, many anomalous results, as those indicated above, may be obtained.

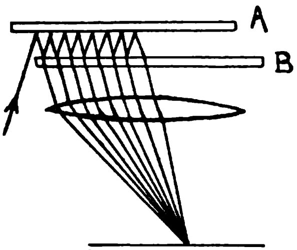


FIG. 3.

RESULTS.

On the basis of what has preceded, the following results have been obtained. A number of sources were employed — metallic vapors in vacuum tubes rendered luminous by the discharge from a large induction coil, metallic vapors in a Bunsen flame and in an electric arc, and lastly the electric spark between electrodes of the metals. This latter source was found to be very unsatisfactory. Of the many sources tried, the bright radiation from mercury vapor was the best for obtaining observations on the changes produced in the components by external changes in the conditions. We will thus first consider the results with this source. Great pains were always taken to have perfect adjustments, chiefly with respect to the focusing of the telescope and the parallelism of the interference plates, before any readings were taken.

The vacuum tube discharge was obtained in a Geissler tube with mercury electrodes, of the form suggested by Runge and Paschen,[1] the capillary of which was placed directly in front of the slit of the spectroscope. The different tubes were connected to a Geryk pump and a pressure-gauge, enabling the pressure of the vapor through which the discharge passed to be quickly changed from a few millimeters to a fraction of a millimeter.

It is rather difficult to decide what is the most advantageous way to record results — whether to take what appears to be the center of gravity of the various components constituting the radiation as the position from which to measure wave-lengths, which is the usual way in the measurements of the lines obtained by means of the grating, or to consider the components of the greatest intensity as the standard and record the wave-lengths of the other components with reference to this. This latter method is the one employed by Michelson, and Fabry and Perot. Nevertheless, it is unsatisfactory, for I have found, even in some of the few radiations investigated, that there are two or more bright components whose intensities are equal. For want of a satisfactory standard, and also that the following results may be easily compared with those of the other investigators, their method, has, however, been followed. In the cases where the brightest components are of equal intensity, one of them has been selected for the standard. In what follows, the plus sign indicates that the component has a longer wave-length than the standard, the minus sign the reverse.

The following results were obtained after a long series of observations with a tube whose capillary was 0.5 mm in diameter and the vapor at a pressure of 1.5 mm. The bright green radiation whose wave-length is 5461 consists of six components. The

		Intensity
1	Standard component	1
2	-1.1×10^{-8} mm	$\frac{3}{4}$
3	-0.9×10^{-8}	$\frac{1}{4}$
4	-0.4×10^{-8}	1
5	$+0.1\times 10^{-8}$	$\frac{1}{8}$
6	$+0.4\times 10^{-8}$	$\frac{1}{4}$

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[1] ASTROPHYSICAL JOURNAL 15, 238, 1902.

two brightest having about equal intensities, the one having the longer wave-length will be considered the standard. The other components have the above differences in wave-length and in intensity relative to the one selected.

Thus there are three components on the side toward the shorter, and two toward the longer wave-lengths.

The violet line, λ4358, is a triple having slight components on each side of the principal.

		Intensity
1...........	Standard component	1
2...........	-0.5×10^{-8} mm	$\frac{1}{4}$
3...........	$+0.4\times10^{-8}$	$\frac{1}{4}$

Both the yellow lines have numerous components, but they are of very slight intensity, so that concordant results were not obtainable.

When a small amount of air was allowed to enter the vacuum tube till the pressure was about 5 mm, the components of small intensity completely disappeared, the fringes due to the brighter components broadened, and their edges became less sharply defined, showing that the atomic vibrations were not so uniform and simple as before. The same effect was noticed with the radiation from a vacuum tube which had been used some time without any change of pressure. In the case where the pressure is changed through the introduction of air, the molecular collisions may be made more frequent, which would naturally interfere with the free vibrations of the atomic systems, and so produce a broadening of the bands and cause the less intense fringes to disappear. In the case of an old tube, when the pressure has not changed, there seems to be no other explanation for the observations than that the mercury vapor had become contaminated with gases driven off from the glass by the heat developed in the discharge.

Whether the atomic vibrations in a source are changed on account of the presence of molecules of foreign matter is an open question. Michelson[1] thinks that the presence of other molecules does not have any appreciable effect except to diminish the visibility. In the case of mercury, when the pressure was high he obtained visibility curves quite different from those obtained when the pressure was low. When the mercury was placed in an atmosphere of hydrogen, the characteristics of the visibility curves were not changed. My results show, however, that when mercury is placed in the presence of air, both in the vacuum tube discharge and in the arc, which will be described later, the appearance of the interference bands is clearly changed, which can be due only to a change in the oscillations of the atomic systems. Schuster, in a lecture at the Royal Institution in 1881, drew from his results this conclusion: "Placing a molecule in an atmosphere of a different nature—without change of temperature—produces the same effect as would be observed in lowering the temperature." In a note to the ASTROPHYSICAL JOURNAL[1] he says: "Something similar seems to take place as regards pressure, for the sodium lines may be obtained wide or narrow according as the atmosphere producing the pressure consists of sodium molecules only or of molecules of a different nature." The results here obtained seem to corroborate those of Schuster.

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[1] *Phil. Mag.*, 34, 280, 1892.

As being of some importance in this subject, I have introduced Figs. 14 and 15, Plate XX, showing the broad bands of the sodium lines, separated and superimposed, obtained with a sodium flame in air as the source. With sodium in a vacuum tube discharge, these bands are as sharp as those of the mercury fringes on Plate XIX. Fig. 13 was obtained with the green radiation from mercury in a tube which had been used a considerable time. The separation of the plates was 6 mm. Here not even one component is visible. A comparison of this photograph with that of Fabry and Perot reproduced in the ASTROPHYSICAL JOURNAL, May 1901, may interest the reader. This reproduction is of the fringes of the same line, with the same separation of plates, but shows the components. Figs. 13, 14, 15, Plate XX, have been magnified about four times. Fig. 16 has not been magnified, and shows how sharp the bands are when the plates are separated 1 cm.

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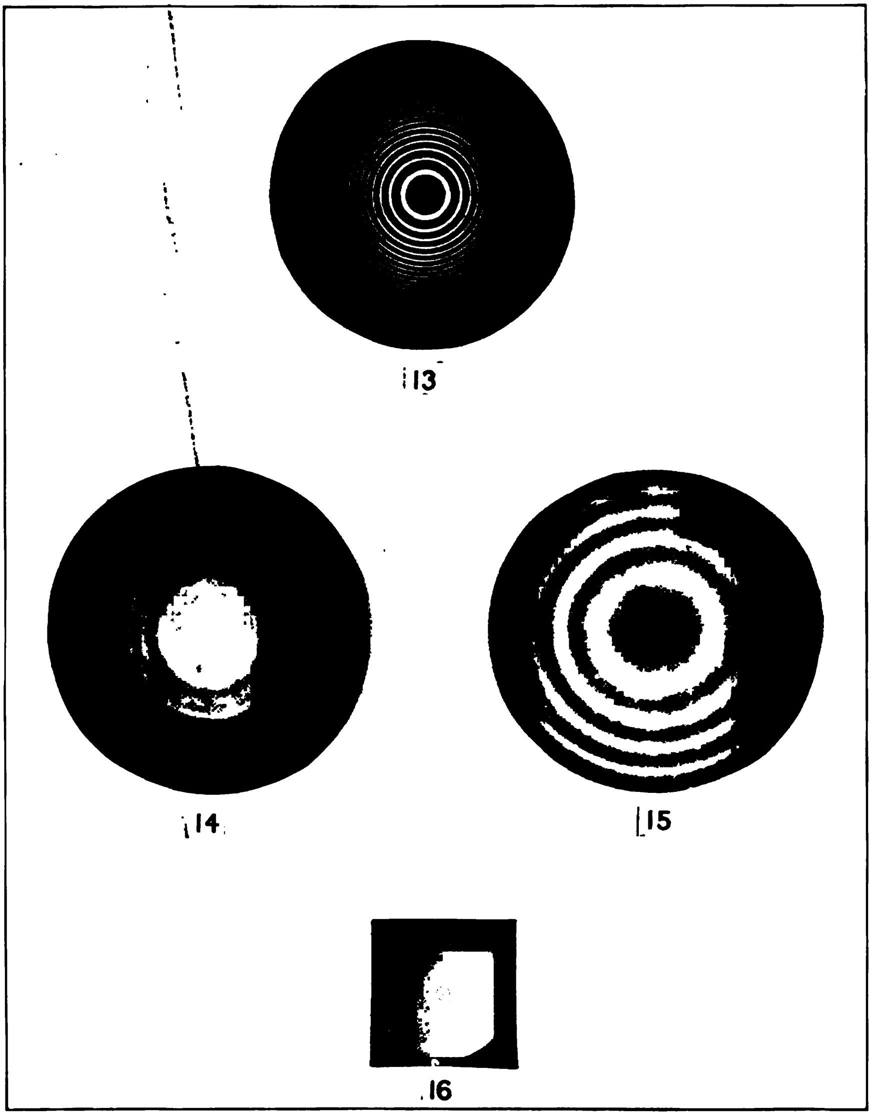
[1] ASTROPHYSICAL JOURNAL, 3, 292, 1896.

PLATE XX.



INTERFERENCE FRINGES.

FIGS. 13 and 16, green mercury line.
FIGS. 14 and 15, sodium lines.

Here also the components of the mercury green radiation are invisible.

With tubes containing capillaries whose diameters are greater than 2 mm the light obtained with an ordinary discharge is not sufficiently intense to show the finer components. The components that can be seen have their edges quite sharp, showing that the vibrations in these tubes are probably the same as in the tubes of smaller capillaries. The finer the capillary, the greater the electrical resistance to the discharge, and hence a rise in temperature, causing a brighter light. Temperature is an important factor, for by heating only the capillary of a tube where there is no liquid mercury present, and thus producing no noticeable change in the pressure in the vacuum tube, the kinetic energy of the atomic aggregations is increased such that many of the components of small intensity, invisible before, are now very readily seen.

The number and intensity of the components were the same whether the tube was placed "side on" or "end on;" that is, whether the discharge was perpendicular or parallel to the propagation of the light through the slit.

The introduction of capacity in parallel with the discharge circuit had an interesting effect. With three large Leyden jars, each a gallon jar, the fringes were broadened and the finer components disappeared. The effect appeared in every way analogous to that obtained when the pressure was increased.

The next step was to investigate the radiations from a mercury arc and to compare the results with those above. After many trials with different kinds of arcs, the following form (Fig. 4) was found the most satisfactory. The arc is between two mercury surfaces. *A* is an ordinary glass receiver of about 800 cu. cm capacity. Over the mouth *B* is sealed a piece of plate glass; through the rubber stopper *C* is run a glass tube which is connected to the Geryk pump. Through the stopper *D* is placed an iron tube *E* of diameter 13 mm. Along the axis of this is placed a porcelain tube *F* of diameter 8 mm. This porcelain tube is connected with a glass tube, which in turn is connected with a large rubber tube. The mercury fills the space between the porcelain and iron tubes as well as the porcelain, glass, and rubber tubes attached. The electric poles are placed as shown in the figure. By raising the barometer column until a drop of mercury flows over into *E* the arc is started. Any further adjustments are easily carried out by raising or lowering the mercury column. Since all the joints were made air-tight, the pressure could be varied by means of the pump. Within a few seconds after the arc is started the whole bulb of the receiver is covered with a layer of mercury thrown off from the arc. This does not penetrate into the neck, so that the glass at *B* is always clear, and the radiation from the arc passes through to the slit of the spectroscope without loss. The whole apparatus may be placed in a cold-water bath to keep the joints cool. This was found unnecessary with the apparatus used even when the arc was steadily run as long as ten minutes. Usually 110 volts were employed, the current was varied by means of a rheostat, and generally 4 amperes were used.

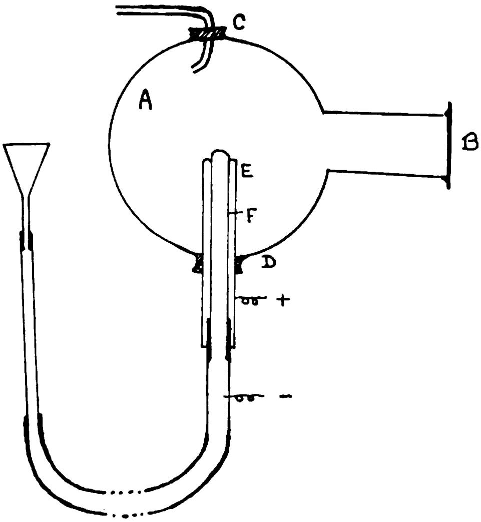


FIG. 4.

With the pressure under 5 mm the results were the same as those obtained with vacuum tubes, as given above. Above this pressure it was very difficult to obtain any components, and the bands were broad and hazy. This is probably due, as above, to pressure and the presence of a number of molecules of air.

The results obtained with the other metallic vapors and gases are briefly as follows:

Cadmium.—Small pieces of metallic cadmium were inclosed in a Geissler tube surrounded by an asbestos jacket. When heated with a Bunsen flame, the metal easily vaporized.

The red line, λ 6439, is nearly monochromatic. There is, however, a weak component toward the shorter wave-lengths:

		Intensity
1…………	Standard component	1
2…………	-0.1×10^{-8} mm	$\frac{1}{5}$

The green line, λ 5086, is composed of four components, the three weaker being on the side toward the larger wave-lengths:

		Intensity
1…………	Standard component	1
2…………	$+0.4 \times 10^{-8}$ mm	$\frac{1}{4}$
3…………	$+0.25 \times 10^{-8}$	$\frac{1}{4}$
4…………	$+0.1 \times 10^{-8}$	$\frac{1}{8}$

The blue line, λ 4800, has a component on each side of the principal:

		Intensity
1…………	Standard component	1
2…………	$+0.6 \times 10^{-8}$ mm	$\frac{1}{5}$
3…………	-0.4×10^{-8}	$\frac{1}{4}$

Thallium.—A piece of metallic thallium was placed on the end of a platinum wire and held in a Bunsen flame. The only bright radiation was that of the green line, λ 5439. A doubling of bands occurred when the plates were separated only a few millimeters. With a vacuum-tube radiation, another component was found with wave-length between the principal and first component:

		Intensity
1…………	Standard component	1
2…………	$+1.0 \times 10^{-8}$ mm	$\frac{3}{4}$
3…………	$+0.4 \times 10^{-8}$	$\frac{1}{4}$

Hydrogen.—By the kindness of Dr. Parsons, I used one of his tubes containing hydrogen which was specially pure, the pressure being 1 mm. The red line easily breaks up into three components, one on each side of the brightest component:

		Intensity
1..........	Standard component	1
2..........	$+0.6 \times 10^{-8}$ mm	$\frac{1}{4}$
3..........	-0.2×10^{-8}	$\frac{1}{8}$

The green line is very complex. The components are so numerous that observations are very difficult.

The changes in the components due to changes in pressure, size of capillary, capacity in circuit, which were examined principally with the mercury radiations, were in some cases tried with the other radiations considered, and the results were in general the same. The above results, with respect to the relative wave-length and intensity of the components under the conditions specified, are collected in the following table, together with the results of Michelson, and Fabry and Perot, upon the same radiations obtained in vacuum tubes. Michelson's values are taken from the curves given in his paper. His method does not allow the determination as to whether the components have longer or shorter wave-lengths than the standard. The second list of values for the components of the mercury line, $\lambda = 5461$, obtained by Fabry and Perot are taken from a paper by Zeeman.[1]

MICHELSON		FABRY AND PEROT		AUTHOR	
Constitution and Separation (× 10^8 mm)	Intensity	Constitution and Separation (× 10^8 mm)	Intensity	Constitution and Separation (× 10^8 mm)	Intensity
		Mercury, $\lambda = 5461$			
		I			
1. Stand. compon...	1	1. Stand. compon..	1	1. Stand. compon..	1
2. 1.2	$\frac{1}{10}$	2. +0.9	$\frac{1}{6}$	2. −1.1	$\frac{3}{4}$
3. 1.0	$\frac{1}{4}$	3. +0.1	$\frac{1}{3}$	3. −0.9	$\frac{1}{4}$
4. 0.7	$\frac{1}{10}$	II		4. −0.4	1
With two weak components near standard.		1. Stand. compon..	1	5. +0.1	$\frac{1}{8}$
		2. −2.2	$\frac{1}{2}$	6. +0.4	$\frac{1}{4}$
		3. −0.7	$\frac{1}{4}$		
		4. −0.5	$\frac{1}{8}$		
		5. +0.1	$\frac{1}{2}$		
		6. +0.8	$\frac{1}{3}$		
		7. +1.3	$\frac{1}{1}$		

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[1] ASTROPHYSICAL JOURNAL, **15**, 218, 1902.

MICHELSON		FABRY AND PEROT		AUTHOR	
Constitution and Separation (×10⁸ mm)	Intensity	Constitution and Separation (×10⁸ mm)	Intensity	Constitution and Separation (×10⁸ mm)	Intensity
Mercury, λ = 4358					
1. Stand. compon...	1			1. Stand. compon..	1
2. 1.7	1/10			2. −0.5	1/4
With two weak components near standard.				3. +0.4	1/4
Cadmium, λ = 6439					
No components		No components		1. Stand. compon..	1
				2. −0.1	1/5
Cadmium, λ = 5086					
1. Stand. compon...	1	1. Stand. compon..	1	1. Stand. compon..	1
2. 0.2	1/5	2. −0.3	1/8	2. +0.4	1/4
				3. +0.25	1/4
				4. +0.1	1/8
Cadmium, λ = 4800					
1. Stand. compon...	1	1. Stand. compon..	1	1. Stand. compon..	1
2. 1.0	1/8	2. +0.8	1/8	2. +0.6	1/5
		3. −0.8	1/8	3. −0.4	1/4
Thallium, λ = 5439					
1. Stand. compon...	1	1. Stand. compon..	1	1. Stand. compon..	1
2. 1.2	1/8	2. +1.1	1/2	2. +1.0	3/4
3. 1.0	1/2	3. +0.2	1/2	3. +0.4	1/4
4. 0.2	1/8				
Hydrogen, λ = 6563					
1. Stand. compon...	1			1. Stand. compon..	1
2. 1.4	3/4			2. +0.6	1/4
				3. +0.2	1/8

After the many long and tedious observations, together with the study and elimination of the errors which may enter into the results due to imperfect adjustments of the apparatus, the author regrets that he is unable to present a more detailed account of the variations that occur in these component radiations, or satellites, as they have been called. The changes occur so suddenly on the least change of the surrounding conditions, and sometimes even when no changes apparent to the observer were introduced, that only qualitative results of a very general nature can be expressed.

During the observations upon the sharp interference fringes due to the mercury green radiation in the two cases, when the components were visible, as exemplified by the photograph given by Fabry and Perot, referred to above, and when, with the same separation of the silvered plates, the components were not present, as exemplified by Fig. 13, the question arose: Has the change in the conditions given birth to one or more satellites? The sharpness of the fringes in both cases; the unequal change in the intensity of the various components under variable conditions, as is shown when the capillary of a vacuum tube is heated; and the fact that the results given in the above table upon the distances between the components are in poor agreement, which is probably due to the different circumstances surrounding the radiation, all point to the possibility of the production of satellites. It must not be forgotten, however, that at the separation of the plates necessary to show the presence of the components, the interference bands are very close to one another, so that it is impossible in this method for an interference fringe due to the birth of a satellite to appear without overlapping some part of the interference fringes of the other components, and hence to produce a new distribution of light in the interference pattern which would naturally lead to different results.

The investigation of the variations in the wave-length and intensity of radiations separated by the grating on account of variation in pressure, electrical condition of the discharge, and the chemical nature of the dielectric surrounding the luminous substance, is at present a very fruitful field; for these changes in these widely separated lines lend themselves to measurement. It is hoped that a method will be found which will more readily show and give measurements of the many changes that occur in radiations whose wave-lengths, and hence their frequencies, do not differ greatly, so that ultimately some knowledge may be obtained as to the mechanics of the systems of moving electrons constituting the atom whose periods differ by small amounts relative to those obtainable at present. A step in this direction has been made by Lummer. The reproductions in the *Ann. d. Phys.*, **10**, 473, 1903, show excellently the complicated structure of these bright radiations. The method proposed above, employing longer plates, is worthy of a fair trial.

My heartiest thanks are due to the professors and lecturers in physics in this University, especially to Professor Ames and Professor Wood, and also to my fellow-students, whose kind assistance in word and deed has greatly facilitated these experiments.

PHYSICAL LABORATORY,
JOHNS HOPKINS UNIVERSITY,
February 1904.

DEFINITIVE ORBIT OF THE SPECTROSCOPIC BINARY *ι PEGASI*.[1]

By HEBER D. CURTIS.

THE spectroscopic binary *ι Pegasi* was discovered by Director Campbell and announced by him in the ASTROPHYSICAL JOURNAL for May 1899. It is of Type F, with fairly good lines. The forty-three plates upon which this orbit depends include all the plates of this star which have been taken with the Mills Spectrograph, with the exception of a few of poor focus or of insufficient exposure, which have been rejected. All the plates have been measured and reduced by the writer, except in the case of Plate 11, where the observed velocity is the mean of measures by Dr. H. M. Reese and the writer. Seven of the plates have been given half weight, generally because depending upon a smaller number of lines.

The following table gives the Greenwich Mean Times of the plates used in the discussion, the observed velocities, and the weights where they differ from unity:

No. of Plate	G. M. T.	Obs. Vel.	Residuals (Prelim. Orbit)	Weight
1..........	1897, Oct. 7.692	−50.0	−0.59	
2..........	1898, Aug. 19.822	−45.0	−1.18	
3..........	20.718	−38.3	−0.09	½
4..........	Sept. 28.703	−23.7	−0.55	
5..........	1899, June 11.998	−43.7	−0.01	
6..........	13.992	−43.2	−1.41	
7..........	July 2.939	−50.9	−1.25	
8..........	26.884	+12.1	−1.46	
9..........	Aug. 1.902	−41.8	−0.90	
10..........	Sept. 20.729	−10.2	+1.34	
11..........	21.684	−36.6	−1.14	
12..........	26.727	+26.3	−1.62	
13..........	27.684	+39.7	−2.45	
14..........	Oct. 3.712	−51.2	−1.40	½
15..........	9.666	+29.6	+2.88	½
16..........	17.669	+35.9	−1.97	
17..........	24.768	−42.5	−0.89	
18..........	25.724	−20.0	−1.45	

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[1] Also to appear as a *Bulletin* of the Lick Observatory.

No. of Plate	G. M. T.	Obs. Vel.	Residuals (Prelim. Orbit)	Weight
19..........	31.673	−13.8	+0.16	
20..........	1902, July 20.895	−46.0	+0.85	½
21..........	Aug. 12.941	−23.1	−1.63	
22..........	17.926	+18.2	+2.96	½
23..........	18.949	−12.5	+0.32	
24..........	19.910	−36.5	+0.02	
25..........	25.798	+40.9	−0.76	
26..........	Sept. 14.876	+37.7	−0.25	
27..........	28.915	−15.5	+0.45	½
28..........	Oct. 8.888	− 6.8	+2.43	
29..........	Nov. 4.697	+34.2	+0.08	
30..........	1903, Jan. 3.603	− 1.3	−0.01	
31..........	4.620	+26.0	−0.78	
32..........	12.613	−35.7	−0.73	
33..........	14.608	+21.4	+0.21	
34..........	18.608	+ 3.8	+1.57	½
35..........	May 12.979	−44.4	+1.18	
36..........	18.008	+37.7	−0.46	
37..........	25.000	−42.9	−0.21	
38..........	27.958	+33.3	−0.72	
39..........	July 8.904	+44.2	+0.75	
40..........	12.982	−42.0	−0.70	
41..........	26.889	− 1.6	−0.94	
42..........	Aug. 10.947	+ 1.5	+1.33	
43..........	Dec. 1.677	−10.6	−0.03	
		$(pvv) =$	51.14	

The residuals in the preceding table were found from a preliminary orbit, using the formulæ and notation of Lehmann-Filhés (*A. N.*, **136**, 17, 1894). This orbit is as follows:

PRELIMINARY ELEMENTS.

Velocity of system = − 3.91 km
T = 1899, June 15.515
= Julian Day 2414821.515
$e = 0.0205$
$\omega = 272^\circ.732$
$\log \mu = 9.78864$
$\log \kappa = 1.67574$
Period = $10^{d}.2132$

From these elements the differential coefficients were computed and the equations of condition formed, introducing a sixth unknown with the coefficient unity for the change in the assumed velocity of the system. After weighting, these coefficients were rendered homogeneous by the introduction of the following factors:

$$x = \delta V$$
$$y = 30.34\ \delta T$$
$$z = 73420\ \delta\mu$$
$$u = \delta\kappa$$
$$v = 48.30\ \delta\omega$$
$$w = 47.60\ \delta e$$

log unit error = 0.3892

From this process were derived the following equations of condition (coefficients natural numbers):

Number	*a*	*b*	*c*	*d*	*e*	*f*	*n*
1	−1.000 *x*	−0.270 *y*	−0.112 *z*	−0.958 *u*	−0.259 *v*	−0.581 *w*	−0.241 = 0
2	−1.000	−0.513	−0.103	−0.536	−0.516	−0.924	−0.482
3	−0.707	−0.458	−0.089	−0.508	−0.408	−0.699	−0.024
4	−1.000	−0.847	−0.148	0.441	−0.878	−0.695	−0.225
5	−1.000	−0.516	−0.001	−0.534	−0.519	−0.927	−0.004
6	−1.000	−0.590	−0.001	−0.790	−0.609	−0.947	−0.575
7	−1.000	−0.254	−0.003	−0.962	−0.243	−0.553	−0.510
8	−1.000	−0.429	−0.026	−0.370	−0.032	−0.655	−0.596
9	−1.000	−0.558	−0.010	−0.777	−0.596	−0.976	−0.367
10	−1.000	−0.312	−0.010	0.155	−0.949	−0.259	−0.547
11	−1.000	−0.699	−0.045	−0.060	−0.716	−0.974	−0.465
12	−1.000	−0.734	−0.051	−0.074	−0.746	−0.993	−0.661
13	−1.000	−0.223	−0.016	−0.975	−0.245	−0.488	−1.000
14	−0.707	−0.171	−0.013	−0.684	−0.188	−0.312	−0.404
15	−0.707	−0.552	−0.039	−0.450	−0.513	−0.695	−0.833
16	−1.000	−0.459	−0.038	−0.885	−0.479	+0.853	−0.804
17	−1.000	0.543	−0.052	0.748	−0.611	−0.950	−0.363
18	−1.000	−0.949	−0.084	−0.312	−0.452	−0.635	−0.592
19	−1.000	−0.903	−0.084	−0.208	−0.940	−0.359	−0.065
20	−0.707	−0.256	0.217	−0.638	−0.283	−0.503	+0.245
21	−1.000	−0.925	−0.717	−0.373	−0.930	−0.732	−0.665
22	−0.707	−0.548	0.425	−0.259	−0.619	−0.541	+0.853
23	−1.000	−0.907	−0.700	−0.182	0.045	−0.311	−0.131
24	−1.000	−0.180	−0.530	0.083	−0.095	−0.982	+0.008
25	−1.000	−0.255	−0.272	−0.970	−0.280	−0.551	−0.310
26	−1.000	−0.458	−0.365	−0.885	−0.478	−0.852	−0.102
27	−0.707	−0.632	−0.510	−0.175	−0.558	−0.307	−0.131
28	−1.000	−0.917	−0.745	−0.105	−0.955	−0.168	+0.992
29	−1.000	0.541	−0.400	−0.803	−0.600	−0.973	−0.032
30	−1.000	−1.000	−0.571	−0.057	−1.000	−0.004	−0.004
31	−1.000	−0.750	−0.659	−0.749	−0.777	+0.982	−0.318
32	−1.000	0.741	−0.654	−0.657	−0.759	−1.000	−0.298
33	−1.000	0.843	−0.741	−0.534	−0.851	−0.884	+0.086
34	−0.707	0.647	[illegible]	−0.095	−0.674	−0.216	−0.453
35	−1.000	−0.453	−0.434	0.575	−0.452	+0.861	−0.482
36	−1.000	−0.450	−0.432	−0.859	−0.470	−0.842	−0.188
37	−1.000	−0.573	−0.544	−0.819	−0.582	−0.923	−0.086
38	−1.000	0.591	−0.572	−0.842	−0.607	−0.974	−0.295
39	−1.000	[illegible]	−0.158	−1.000	−0.019	−0.031	+0.306
40	−1.000	[illegible]	−0.579	−0.784	0.588	−0.972	−0.286
41	−1.000	−0.444	[illegible]	−0.071	−0.999	−0.092	−0.383
42	−1.000	[illegible]	[illegible]	−0.109	−0.057	−0.221	+0.543
43	−1.000	−0.014	−1.000	0.137	−0.952	+0.223	−0.012

From these were derived the following normal equations:

x	y	z	u	v	w	n	s
+39.499	+ 0.340	+ 1.503	− 3.489	− 0.416	+13.391	−5.163	+45.664
	+19.412	−10.661	− 6.474	−19.863	+ 3.751	+6.954	− 6.540
		+ 9.588	+ 2.790	+10.917	+ 0.114	−4.071	+10.179
			+18.341	+ 6.615	+ 2.435	+0.659	+20.876
				+20.332	− 3.783	−7.164	+ 6.637
					+21.994	−3.338	+34.563
						+9.102	− 3.025

The solution of these equations gives for the values of the unknown quantities and their probable errors:

$\delta V = -0.12$ km ±0.11 km
$\delta T = -0.349$ days ±0.219
$\delta \mu = +0.0000050$ ±0.0000042
$\delta \kappa = +0.564$ ±0.152
$\delta \omega = -0.242$ ±0.0304 radians
$= -13^{\circ}880$ $\pm 1^{\circ}740$
$\delta e = -0.0119$ ±0.0032

giving for the corrected elements:

$V = -4.03$ ±0.11 km
$T = 1899$, June 15.166 ±0.219 days
$e = 0.0086$ ±0.0032
$\omega = 258^{\circ}852$ $\pm 1^{\circ}740$
$\log \mu = 9.7890216$ ±0.0000029
$\mu = 35^{\circ}2488$ $\pm 0^{\circ}0002$
$U = 10.21312$ ±0.00006 days
$\log \kappa = 1.68088$ ±0.00014

The sum of the squares of the weighted residuals has been reduced by this solution from 51.14 to 26.28. On computing an ephemeris from these changed elements, however, and comparing these changes in the residuals with those secured by substitution in the equations of condition, it was found that the differences were considerably larger than could be attributed to the ordinary errors of logarithmic computation, showing that the effect of terms of the second order in the differential coefficients was of appreciable magnitude. A second solution was therefore necessary. Using the ephemeris based upon the second set of elements, and recomputing the differential coefficients, the following set of equations was derived:

Number	*a*	*b*	*c*	*d*	*e*	*f*	*n*
1	$+1.000x$	$+0.285y$	$+0.112z$	$-0.959u$	$-0.279v$	$+0.382w$	$-0.013=0$
2	+1.000	+0.540	+0.103	−0.835	−0.540	+0.824	−0.388
3	+0.707	+0.485	+0.090	−0.504	−0.488	+0.688	−0.018
4	+1.000	+0.896	+0.148	−0.385	−0.908	+0.825	−0.549
5	+1.000	+0.543	+0.001	−0.833	−0.543	+0.828	+0.152
6	+1.000	−0.597	±0.000	−0.802	+0.603	−0.995	−0.326
7	+1.000	+0.265	−0.003	−0.964	−0.259	+0.343	−0.286
8	+1.000	−0.939	+0.025	+0.338	+0.942	+0.777	−0.040
9	+1.000	+0.619	−0.019	−0.775	−0.621	+0.917	−0.295
10	+1.000	+0.960	−0.006	−0.132	−0.975	+0.437	+0.098
11	+1.000	+0.738	−0.046	−0.654	−0.744	+0.993	−0.522
12	+1.000	0.762	+0.050	+0.641	+0.768	+1.000	−0.179
13	+1.000	−0.272	+0.018	+0.959	+0.283	+0.357	−1.000
14	+0.707	−0.176	+0.012	−0.686	+0.183	−0.457	−0.210
15	+0.707	+0.501	−0.037	+0.482	−0.507	−0.679	+0.317
16	+1.000	0.503	+0.040	+0.859	+0.513	+0.765	−0.554
17	+1.000	0.600	+0.050	−0.800	+0.606	−0.996	−0.062
18	+1.000	0.948	+0.080	0.323	+0.948	−0.444	−0.192
19	+1.000	+0.952	−0.084	0.187	−0.967	+0.533	−0.380
20	+0.707	+0.296	−0.214	−0.640	−0.294	+0.447	+0.460
21	+1.000	−0.927	+0.683	−0.378	+0.927	−0.547	−0.388
22	+0.707	+0.615	−0.455	+0.309	−0.675	−0.461	+0.402
23	+1.000	+0.955	−0.707	−0.165	−0.970	+0.496	−0.228
24	+1.000	+0.714	−0.529	−0.681	−0.719	+0.987	+0.098
25	+1.000	−0.302	+0.225	+0.950	+0.312	+0.414	−0.281
26	+1.000	−0.497	+0.370	+0.863	+0.507	+0.756	+0.156
27	+0.707	+0.666	−0.511	−0.165	−0.677	+0.431	−0.080
28	+1.000	+0.964	−0.745	−0.090	−0.980	+0.359	+0.661
29	+1.000	−0.622	+0.491	+0.777	+0.631	+0.917	+0.406
30	+1.000	−1.000	+0.828	+0.036	+1.000	+0.268	+0.451
31	+1.000	−0.778	+0.645	+0.621	+0.785	+1.000	+0.112
32	+1.000	−0.754	+0.629	−0.657	+0.758	−0.944	−0.058
33	+1.000	−0.859	+0.717	+0.506	+0.803	+0.953	+0.536
34	+0.707	+0.675	−0.566	+0.112	0.687	−0.890	+0.080
35	+1.000	+0.470	−0.428	0.879	−0.468	+0.719	+0.790
36	+1.000	−0.488	+0.446	+0.868	+0.498	+0.741	+0.045
37	+1.000	0.576	+0.529	−0.818	+0.582	−0.989	+0.165
38	+1.000	0.623	+0.573	+0.777	+0.631	+0.917	+0.036
39	+1.000	−0.004	+0.003	+0.998	+0.012	−0.186	+0.134
40	+1.000	+0.605	0.575	−0.787	−0.607	+0.905	−0.112
41	+1.000	1.000	+0.958	+0.050	+1.000	+0.295	+0.018
42	+1.000	+0.961	−0.930	+0.113	−0.955	−0.035	+0.045
43	+1.000	+0.961	−1.000	0.120	−0.977	+0.416	−0.371

As in the first solution, these equations have been made homogeneous by the factors

$$x=\delta I'$$
$$y=29.98\delta T$$
$$z=76350\delta\mu$$
$$u=\delta\kappa$$
$$v=48.33\delta\omega$$
$$w=48.11\delta e$$

log unit error $=0.3502$

The following normal equations result from the equations of condition given above:

x	y	z	u	v	w	n	s
+39.499	+ 0.541	+ 1.470	− 3.640	− 0.531	+13.337	− 1.648	+49.027
	+20.822	−10.772	− 6.618	−20.995	+ 3.711	− 0.343	−13.653
		+ 9.262	+ 2.665	+10.859	+ 0.313	+ 0.110	+13.906
			+17.953	+ 6.683	+ 2.279	+ 0.439	+19.760
				+21.172	− 3.711	+ 0.337	+13.812
					+21.743	− 0.635	+37.036
						+ 5.339	+ 3.598

VALUES OF UNKNOWNS—SECOND SOLUTION.

$\delta V = -0.09$ ±0.11 km
$\delta T = -0.200$ ±0.352 days
$\delta \mu = +0.00000007$ ±0.00000407
$\delta \kappa = +0.0327$ ±0.1523
$\delta \omega = -0.1230$ ±0.0240 radians
$\delta e = -0.00008$ ±0.0040

FINAL ELEMENTS

$V = -4.12$ ±0.11 km
$T =$ 1899, June 14.966 ±0.352 days
= J. D. 2414820.966
$e = 0.0085$ ±0.0040
$\omega = 251\overset{\circ}{.}807$ $\pm 1\overset{\circ}{.}373$
$\log \kappa = 1.68117$ ±0.00014
$\log \mu = 9.7890216$ ±0.0000029
$\mu = 35\overset{\circ}{.}2488$ $\pm 0\overset{\circ}{.}0002$
Period = 10.21312 ±0.00006 days
$a \sin i = 6{,}740{,}000$ km

This solution is satisfactory, as may be seen from the accompanying table, in which are given the residuals from the two solutions and the comparisons of these residuals with the values found by substitution in the equations of condition.

No.	First Solution		Second Solution		Weight
	Resid.	Eph.−Eq.	Resid.	Eph.−Eq.	
1	−0.03	+0.10	+0.11	+0.01	½
2	−0.87	−0.16	−0.71	+0.04	
3	−0.05	+0.03	+0.09	+0.02	
4	−1.23	−0.07	−1.15	−0.01	
5	+0.34	−0.16	+0.49	+0.02	
6	−0.73	−0.22	−0.62	+0.01	
7	−0.64	−0.23	−0.47	+0.02	
8	−0.09	+0.04	−0.04	−0.02	
9	−0.66	−0.13	−0.52	+0.03	

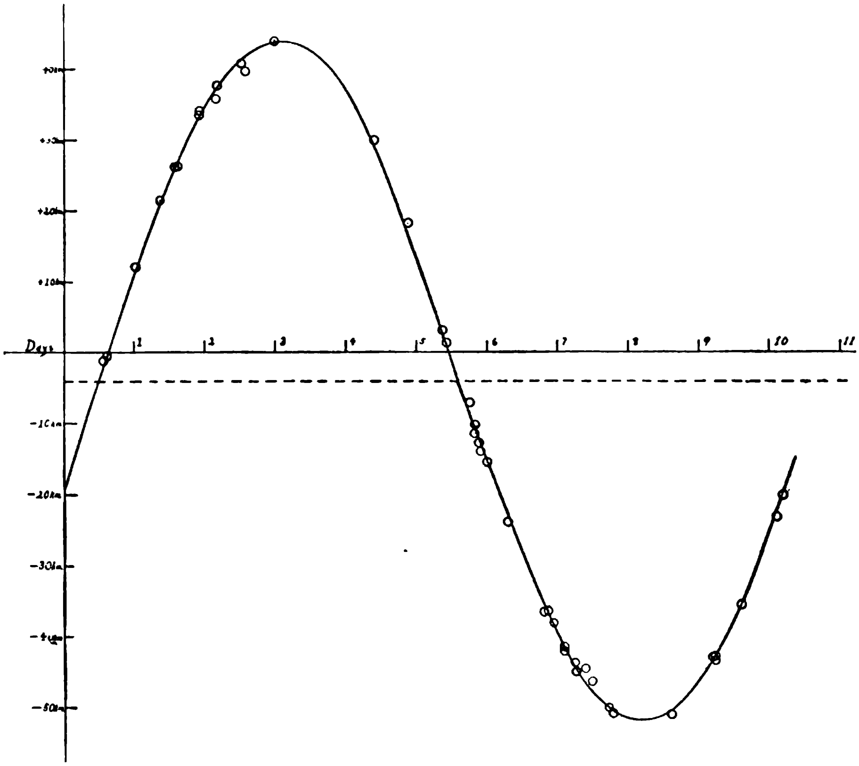
No.	First Solution		Second Solution		Weight
	Resid.	Eph. − Eq.	Resid.	Eph. − Eq.	
10	+0.22	−0.06	+0.28	−0.02	
11	−1.17	−0.10	−1.04	+0.02	
12	−0.40	+0.01	−0.33	−0.01	
13	−2.24	−0.14	−2.14	0.00	
14	−0.67	−0.15	−0.51	+0.03	
15	+1.00	−0.12	+1.05	−0.02	½
16	−1.24	−0.10	−1.13	+0.02	½
17	−0.14	−0.14	−0.03	+0.01	
18	−0.43	+0.02	−0.38	−0.01	
19	−0.85	−0.04	−0.78	−0.01	
20	+1.45	−0.13	+1.62	+0.04	½
21	−0.87	+0.02	−0.82	−0.02	
22	+1.27	−0.06	+1.32	−0.02	½
23	−0.51	+0.05	−0.45	−0.01	
24	+0.22	−0.13	+0.35	+0.01	
25	−0.63	−0.24	−0.52	+0.01	
26	+0.35	−0.12	+0.47	+0.01	
27	−0.25	−0.04	−0.19	−0.02	½
28	+1.48	+0.12	+1.54	−0.02	
29	+0.91	+0.11	+1.00	−0.02	
30	+1.01	−0.01	+1.03	+0.01	
31	+0.25	−0.06	+0.32	−0.03	
32	−0.13	−0.17	−0.04	0.00	
33	+1.20	−0.03	+1.27	−0.02	
34	+0.25	−0.18	+0.29	+0.01	½
35	+1.77	−0.11	+1.94	−0.02	
36	+0.10	−0.11	+0.21	+0.05	
37	+0.37	−0.12	+0.48	+0.02	
38	+0.08	−0.06	+0.17	0.00	
39	+0.30	−0.18	+0.41	+0.01	
40	−0.25	−0.13	+0.10	+0.04	
41	+0.04	+0.14	+0.08	−0.02	
42	+0.10	−0.05	+0.14	0.00	
43	−0.83	−0.04	−0.78	−0.03	

The probable error of a single plate derived from this solution is ±0.56km. The relatively large probable errors in the values of T and ω arise from the fact that the orbit is so nearly a circle, the eccentricity being only +0.0085. On the other hand, inasmuch as the observations cover two hundred and nineteen complete revolutions of the star, the period is determined with considerable accuracy.

The accompanying diagram shows the curve of the final orbit and the observed places as derived from the plates, which are represented by small circles. The largest residual is −2.14km;

the range of velocity is from +43.7 to −52.1 km per second. The dotted line represents the velocity of the center of mass of the system.

There is no evidence on any of the plates of a second spectrum from which to make an estimate of the relative velocities in the system. Dr. R. G. Aitken states that he examined *ι Pegasi* in 1901 with the 36-inch refractor, but found no evidence of duplicity.



Velocity-Curve of *ι Pegasi.*

LICK OBSERVATORY,
March 4, 1904.

MINOR CONTRIBUTIONS AND NOTES.

VARIABILITY OF *IRIS* (7).[1]

A SERIES of measurements of the light of the planet *Iris* (7) has been made by Professor Wendell with the polarizing photometer, with sliding achromatic prisms, attached to the fifteen-inch equatorial telescope of the Harvard College Observatory. A variation like that of the planet *Eros* has been established, having a period of about $0^d.259 = 6^h\ 13^m$. The range is only two or three tenths of a magnitude, and the variation would be uncertain but for the very small accidental errors which occur in observations made in this way. See *Circulars* Nos. 23, 25, 30, and 41.

The results of the measures made by Professor Wendell are given in Table I. The Julian Day and fraction following Greenwich Mean Noon, omitting the three left-hand figures, 241, is given in the first column. The designation of the comparison star is given in the second column. The observed difference in magnitude between *Iris* and the comparison star is given in the third column, a positive sign indicating that the star was brighter than *Iris*. The fourth column gives the phase computed by the formula $2,416,470^d.000 + 0^d.259$ E. The fifth column gives the amount that *Iris* is fainter than its assumed maximum magnitude. This quantity was found by plotting the times and observed differences in magnitude on each night, and by inspection assuming the maximum magnitude. The latter was then subtracted from the observed magnitude, and a curve constructed from these differences and the corresponding phases. Owing to errors in the assumed maximum magnitudes, the points on some nights were above and on others below the curve. The mean value of the deviations from the curve for each night was therefore subtracted from these differences and gives the quantity contained in the fifth column. Negative signs are indicated by *italics*. This process was necessary, since different stars was used on different nights, and we had no means of knowing their true magnitudes. The sixth column gives the residual found by subtracting the magnitude as given by a smooth curve from that contained in the fifth column. The average value of these forty-six residuals is only ± 0.022.

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[1] *Harvard College Observatory Circular* No. 70.

TABLE I.

Observations of *Iris* (7).

J. D.	*B. D.*	Diff.	Phase	M.	O.−C.
6475.606	+18°1576	−0.79	0.167	0.22	0.03
.612	" "	−0.86	0.173	0.15	*0.02*
.658	" "	−1.01	0.219	0.00	*0.01*
.665	" "	−1.02	0.226	*0.01*	*0.02*
6477.645	+18 1553	−0.96	0.134	0.06	*0.02*
.651	" "	−0.90	0.140	0.12	0.02
.662	" "	−0.86	0.151	0.16	0.00
6479.603	+18 1538	+0.12	0.020	0.21	0.02
.611	" "	+0.11	0.028	0.20	*0.01*
.656	" "	−0.02	0.073	0.07	0.04
.664	" "	−0.07	0.081	0.02	0.00
6480.552	" "	−0.08	0.192	0.05	*0.02*
.558	" "	−0.13	0.198	0.00	*0.04*
.586	" "	−0.07	0.226	0.06	0.05
.612	" "	−0.07	0.252	0.06	*0.01*
.621	" "	−0.04	0.002	0.09	*0.03*
6485.565	+18 1496	−1.66	0.025	0.25	0.04
.570	" "	−1.68	0.030	0.23	0.02
.601	" "	−1.83	0.061	0.08	0.00
.606	" "	−1.91	0.066	0.00	*0.04*
.624	" "	−1.88	0.084	0.03	0.01
.631	" "	−1.90	0.091	0.01	*0.01*
.651	" "	−1.86	0.111	0.05	0.00
.660	" "	−1.83	0.120	0.08	0.02
6487.540	+18 1495	−1.68	0.187	0.10	0.00
.546	" "	−1.72	0.193	0.06	0.00
.568	" "	−1.76	0.215	0.02	0.01
.576	" "	−1.76	0.223	0.02	0.01
.599	" "	−1.73	0.246	0.05	0.00
.606	" "	−1.75	0.253	0.03	*0.04*
.627	" "	−1.64	0.015	0.14	*0.04*
.636	" "	−1.59	0.024	0.19	*0.02*
.656	" "	−1.68	0.044	0.10	*0.03*
.664	" "	−1.71	0.052	0.07	*0.01*
6495.567	+18 1419	−1.00	0.185	....	....
.574	" "	−1.02	0.192	....	....
6498.543	+18 1391	−1.99	0.053	0.08	0.00
.551	" "	−2.04	0.061	0.03	*0.02*
6499.524	" "	−1.82	0.257	0.21	0.10
.530	" "	−1.82	0.004	0.21	0.07
.546	" "	−1.80	0.020	0.23	0.03
.552	" "	−1.82	0.026	0.21	0.00
.578	" "	−1.96	0.052	0.07	*0.01*
.585	" "	−1.97	0.059	0.06	0.00
.603	" "	−2.01	0.077	0.02	0.00
.610	" "	−2.08	0.084	*0.05*	*0.07*
.630	" "	−2.03	0.104	0.00	*0.03*
.660	" "	−1.96	0.134	0.07	*0.03*

The co-ordinates of the light-curve are given in Table II. The phases are given in the first and third columns; the corresponding magnitudes, in the second and fourth columns. The differences found by subtracting the numbers in the fourth column from those in the second are given in the fifth column. It will be seen, therefore, that there are two maxima and two minima, which are so nearly equal that it is as yet impossible to say whether the differences are real or due to small systematic errors. In the latter case, the period should be divided by two, and become $0^d.1295 = 3^h\ 6^m$.

It will be seen that the variation closely resembles that of *Eros*, and that the conditions discussed in *Circular* No. 58 apply to *Iris* also. The latter asteroid is bright enough to be readily observed during a large part of the time, but unfortunately the change of light is now so small that it can be determined only by observations in which the accidental errors are extremely small. In fact, the observations of *Iris* made at Potsdam in 1884 (*Publicationen*, 8, 294) fail to show this variation, either because the range was then too small, the period was then different, or the errors of observation rendered the variation imperceptible. The average of the residuals on the twenty-six nights of observation was ±0.073, or about the same as that for the other asteroids. A change in the period seems improbable.

TABLE II.

Light-Curve.

Ph.	M.	Ph.	M.	Diff.	Ph.	M.	Ph.	M.	Diff.
0.00	0.12	0.13	0.09	0.03	0.07	0.03	0.20	0.06	*0.03*
0.01	0.16	0.14	0.12	0.04	0.08	0.02	0.21	0.02	0.00
0.02	0.19	0.15	0.17	0.02	0.09	0.02	0.22	0.01	0.01
0.03	0.21	0.16	0.19	0.02	0.10	0.03	0.23	0.02	0.01
0.04	0.17	0.17	0.18	*0.01*	0.11	0.04	0.24	0.03	0.01
0.05	0.10	0.18	0.14	*0.04*	0.12	0.06	0.25	0.03	0.03
0.06	0.05	0.19	0.09	*0.04*					

The observations contained in Table III was made on January 25, 1904, after the above discussion was completed. *Iris* was compared with +17°.1404, and the Julian Day and fraction, difference in magnitude, and phase are given in the successive columns. It will be seen, by plotting these observations, that they fall almost exactly upon a smooth curve, and that the phase of maximum, $0^d.085$, agrees very nearly with that derived from the previous observations. A change, however, appears to have taken place in the range, which now exceeds three-tenths of a magnitude, or an increase of about one half in a few days. This change is confirmed by the last ten residuals in the last column of Table I, which indicate that the increase in range occurred between J. D. 6487 and J. D. 6499. The change in the range of *Eros* in the spring of 1901 was also much more rapid than might have been expected from geometrical considerations. The range on March 12, 1901, was found to be about 1.0; on April 12, 1901, 0.4; and on May 6 and 7, 1901, 0.0, magnitudes.

Evidently, this object should be watched carefully. It is now favorably situated, as it is approaching its second stationary point, and is of about the eighth magnitude. *Iris* can be conveniently compared photometrically with the stars +17°1339, +17°1355, +17°1364, and +17° 1391, during the next few weeks, and it is hoped that observers elsewhere will connect their observations with these stars and with the comparison stars used in Tables I and III, so that all may be reduced to one system. Measures of the absolute magnitudes of these stars will be undertaken here. It will be noticed that observations on each night should extend over at least three hours. In that case, a maximum and minimum will always be included, so that the absolute magnitudes of the comparison stars will be of less importance.

TABLE III.

Later Observations.

J. D.	Diff.	Ph.	J. D.	Diff.	Ph.
6505.539	−0.52	0.056	6505.610	−0.44	0.127
.546	−0.56	0.063	.619	−0.37	0.136
.562	−0.59	0.079	.636	−0.28	0.153
.569	−0.60	0.086	.645	−0.34	0.162
.585	−0.58	0.102	.656	−0.38	0.173
.592	−0.56	0.109	.662	−0.46	0.179

EDWARD C. PICKERING.

JANUARY 1904.

PUBLICATIONS OF THE YERKES OBSERVATORY.

THE following papers, recently issued by the University of Chicago Press, as THE DECENNIAL PUBLICATIONS of the University of Chicago, are being reprinted in Volume II of the PUBLICATIONS OF THE YERKES OBSERVATORY, and will soon be distributed to correspondents:

I. MEASURES OF DOUBLE STARS WITH THE FORTY-INCH REFRACTOR OF THE YERKES OBSERVATORY IN 1900 AND 1901. *By Sherburne Wesley Burnham.*

II. MICROMETRICAL OBSERVATIONS OF *EROS* MADE WITH THE FORTY-INCH REFRACTOR OF THE YERKES OBSERVATORY DURING THE OPPOSITION OF 1900–1901. *By Edward Emerson Barnard.*

III. ON CERTAIN RIGOROUS METHODS OF TREATING PROBLEMS IN CELESTIAL MECHANICS. *By Forest Ray Moulton.*

IV. RADIAL VELOCITIES OF TWENTY STARS HAVING SPECTRA OF THE *ORION* TYPE. *By Edwin Brant Frost and Walter Sydney Adams.*

V. THE SPECTRA OF STARS OF SECCHI'S FOURTH TYPE. *By George Ellery Hale, Ferdinand Ellerman, and John Adelbert Parkhurst.*

VI. ASTRONOMICAL PHOTOGRAPHY WITH THE FORTY-INCH REFRACTOR AND THE TWO-FOOT REFLECTOR OF THE YERKES OBSERVATORY. *By George Willis Ritchey.*

VII. THE ORBIT OF THE MINOR PLANET (334). *By Kurt Laves.*

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A STUDY OF THE CAUSES OF VARIABILITY OF SPARK SPECTRA.

By A. S. King.

The variability of spark spectra, *i. e.*, the changes in the relative intensities of different lines, was noted by Kirchhoff, and has since been the subject of many researches.

Our present knowledge of the subject, though very incomplete, leads us to consider the causes of variability under the following heads:

1. *Temperature.*—The influence of change of temperature upon the relative intensity of lines was observed soon after the discovery of spectrum analysis. Being closely associated with other changes in physical conditions, especially in spark spectra, it is difficult to say how much of the variation observed may be ascribed to temperature alone. The view has been held that higher temperature most strengthens the lines of shorter wave-length, that it produces a shift of the maximum intensity of the spectrum. Kayser[1] has pointed out that this hypothesis can be applied only to lines originating from the same vibrating body, *i. e.*, to lines connected by a series relation; as on the other lines an increase of temperature may have the opposite

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[1] Astrophysical Journal, 14, 313, 1901.

effect of reducing the intensity by destroying the more complex atomic aggregate from which these lines are derived.

2. *Vapor density.*—A change in the amount of luminous vapor produced may have a twofold effect. It may simply intensify all of the lines because of the increased number of radiating particles; or the strains produced by the greater crowding of the molecules may produce new vibrations and enhance only a part of those already existing. This is in accordance with the well-known fact that, in general, the diffuse lines are more affected by changes in the quantity of vapor.

3. *Electrical conditions.*—It is probable that these may affect the spectrum in very different ways. If oscillations are present, it is conceivable that they produce forced vibrations, strengthening some lines whose period is in some relation to their own. A change in the strength and frequency of the oscillations may be one effect of the introduction of self-induction. It may also produce a change in temperature, but it is an unsettled question whether the temperature is raised or lowered by self-induction. Oscillations may also intensify only the more damped vibrations. Capacity will impart to the spark discharges greater current strength, greater vapor density and probably higher temperature; but at the same time the period of oscillation is altered. A change of electromotive force changes the energy of the luminous particles, their velocity. Higher electromotive force may therefore strengthen the forced vibrations, but by increase of temperature the others also. The greater momentum of the molecules or ions, on the other hand, may help to disintegrate the more complex atomic aggregates.

It is clear, therefore, that altered electrical conditions may produce very great relative differences among spectral lines; but our very limited knowledge of the processes of production of light by electricity makes it difficult, or even impossible, to determine in each special case what effect of changed electrical condition has produced the observed change in intensity.

4. *Surrounding atmosphere.*—This may change the temperature, either by more or less of the electricity being conducted by the gas instead of by the metallic vapor, or through an alteration of

the potential between the electrodes. The same causes would affect the density of metallic vapor. Also, the gas may produce chemical actions, resulting in a change of temperature or of molecular structure.

As in nearly all cases a change in one condition is accompanied by a change in several others, it is extremely difficult to state the true cause of an observed change in intensity. Only by accumulating a great many observations with every possible change of conditions may we be able at last to determine some of the true causes.

My experiments, of which the account is to follow, have been concerned with changes given by self-induction in the spark circuit and by varying capacity; and the changes observed in the spectra probably resulted from a combination of the first three elements mentioned above. We should expect the chief alteration in electrical conditions by self-induction to be a reduction of the strength and frequency of the oscillations, with the reverse change when capacity is increased; though these changes in the circuit must result also in a difference in the interaction of primary and secondary, the effects of which are probably minor in their nature, but are obscure and depend on the construction of the induction coil used.

The metals studied were cadmium, zinc, magnesium, calcium, mercury, and aluminum. These are especially favorable for such work, each of them containing groups of related lines and other lines which are very sensitive to changed conditions. The effect of self-induction upon the spectra of some of these metals has been observed more or less extensively by Hemsalech,[1] Schenck,[2] Huff,[3] Néculcéa,[4] Berndt,[5] and Gramont,[6] and some of their results, especially in the way of throwing light upon the electrical processes in the spark, have been of much value in enabling me to form the conclusions toward which my own results point.

My photographs cover the region of the spectrum from λ2100 to λ5700. They were taken with a small Rowland concave grating of 1 m radius, giving a dispersion of 10 tenth-meters to 0.593 mm. The inductance spool used was of rather fine wire, wound in a single layer, and immersed in oil for insulation. Its resistance was 8 ohms and its inductance 0.003 henry.

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[1] Thesis, Paris, 1901.

[2] ASTROPHYSICAL JOURNAL, **14**, 116, 1901.

[3] *Ibid.*, **12**, 103, 1900.

[4] *Comptes Rendus*, **134**, 1494, 1572, 1902; **135**, 25, 1902.

[5] *Ibid.*, **134**, 1048, 1205, 1902.

[6] *Inaug. Dissert.*, Halle, 1901.

The general method of making comparison photographs was to time the exposures with and without self-induction, so as to make the lines least affected by self-induction of approximately the same intensity in the two photographs. The lines more affected would then usually appear in both photographs, and an estimate of the amount by which they were changed could be made with considerable accuracy. The changes considered are thus always relative to the lines least affected, as the weakened intensity of the spark by self-induction always required a longer exposure, the difference of the exposure varying with the metal used.

Leyden jars of 0.0027 microfarad each were used as capacity, with one small jar of 0.0018 microfarad. Both capacity and primary current remained the same in comparing the spark with and without self-induction, but varied for different elements. In comparing the changes given by large and small capacity, the same current was used in the primary for each, and the photographs were timed for favorable comparison in the same way as in testing the effect of self-induction. In some cases, when the same exposure was desired for photographs taken with varying capacity, a hand interrupter was used and the sparks counted, to avoid the change of period of the usual interrupter when the capacity was altered. A spark-length of about 2 mm was used throughout, and, except with calcium, did not change by an appreciable amount while the comparison photographs were being taken. An account of the experimental results follows.

CADMIUM.

The spark was produced between metallic terminals, and in order that the slight oxidation of the electrodes might not introduce an uncertainty in the comparison of two successive photographs, the spark was allowed to pass long enough to give some oxidation before a photograph was taken. The further oxidation was so slight that it could scarcely make an appreciable difference in the rate of vaporization of the metal. This method seemed preferable to cleaning the electrodes before each photograph, as their removal for this purpose would make it impossible to keep exactly the same spark-length and an unchanged image on the slit.

Effect of self-induction.—The introduction of self-induction gives a means of separating the cadmium lines into two main groups, as has been done by Schenck.[1] The weakening action of self-induction is much greater upon "Group B" of Schenck's classification than upon "Group A," the "arc lines." I wish, however, to call attention to some special features in the differences produced by self-induction. My plates show, in the first place, that the lines belonging to the two subseries of Kayser and Runge are all included in Group A; while the prominent non-series lines, which are much more reduced by self-induction, are members of Group B. Further, the triplets of the first subseries are weakened more than the triplets of the second subseries, and this difference between the action on the two series is more pronounced as the wave-length becomes shorter.

Five times as long an exposure with self-induction as without was required to bring corresponding lines of the second subseries to the same intensity. The lines of the first subseries were then about three-fourths as strong as without self-induction,[2] especially noticeable in the triplets λλ2837, 2881, 2981, while the non-series lines λλ2573, 2749, 3250, 4216, 5490 retained about one-eighth of their former intensity, and the strong spark lines λλ5339, 5379 are quite blotted out by self-induction. These photographs are shown in Plate XXI (Figs. 1 and 2).

Effect of varying capacity.—With the same current in the primary of the induction coil and no outside inductance, a comparison was made between the spectrum given with 0.0018 microfarad and that with 0.0027 microfarad capacity. Photographs so timed that the non-series lines were of approximately equal intensity in each gave the series lines only one-half as strong with the higher capacity, showing that the intensity of the non-series lines increases with capacity much faster than that of the series lines—the effect of increased capacity thus being opposite to that of self-induction.

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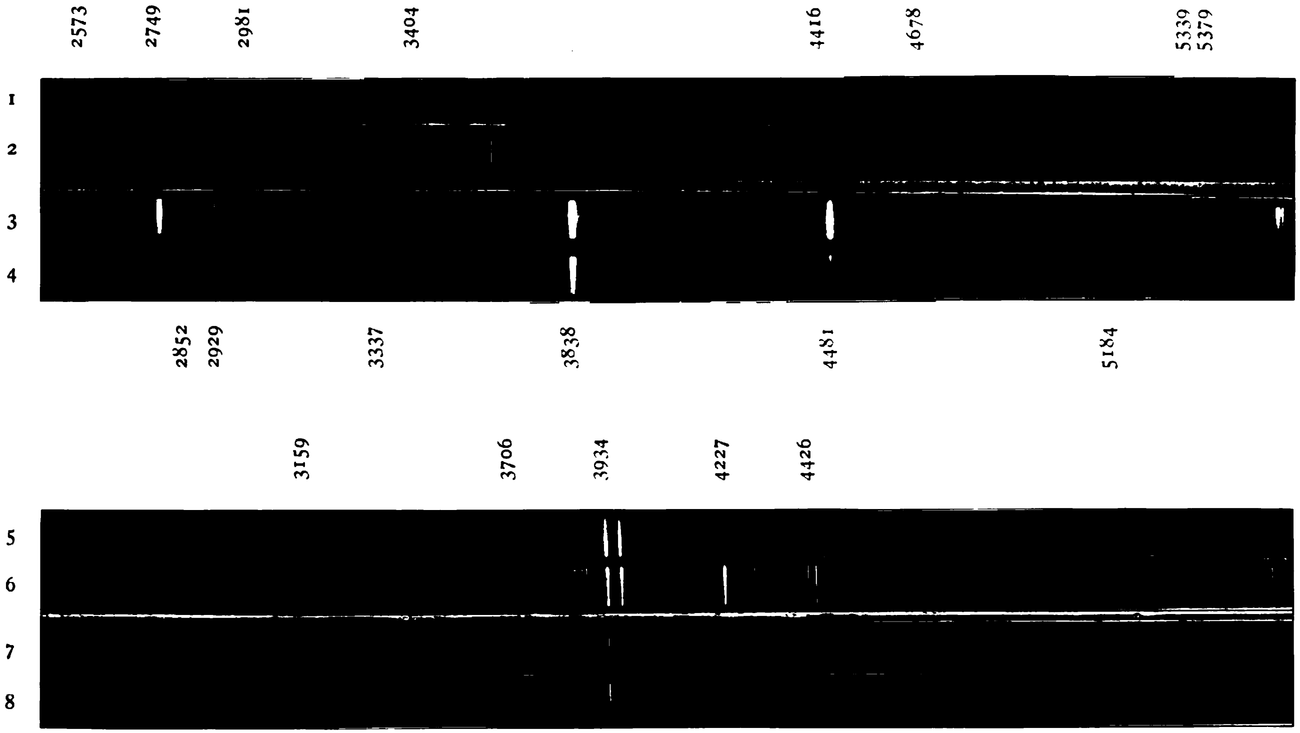
[1] *Loc. cit.*

[2] The comparison of intensities was assisted by the use of a photographic scale. This was made by moving a photographic plate beneath a narrow slit, with an incandescent lamp placed above at such a height that with two seconds' exposure the line on the plate was barely visible. Making each successive exposure 1.7 times the previous one gave a series of lines of increasing blackness. This scale was of much assistance in gauging the intensities of lines, though naturally the character of a line must be considered in estimating its intensity.

In order to see if there is a rule governing this strengthening of the non-series lines by capacity, photographs were taken with one, two, four, and eight Leyden jars, with the same primary current and the same number of sparks for each photograph, this last condition being secured by a hand-interrupter. The chief attention in this comparison was given to the diffuse spark lines λλ 5339, 5379, whose change in intensity could be closely estimated, and which were found by Schenck to be due chiefly to the oscillations in the spark. With such a number of sparks that these lines were barely visible with one jar, the increase for two, four, and eight jars was found to be, as nearly as could be judged, in the same ratio as the change of capacity. The series lines show a very gradual change, being about twice as strong with eight jars as with one. To eliminate the spark at "make," which appears with one jar and not with eight, when the same primary current was used, the spark-length was so adjusted that with four and with eight jars the spark came only at "break," and fewer sparks were used than before. These two photographs could be very accurately compared, and showed that with doubled capacity λλ 5339, 5379 were intensified in the ratio 1 : 2, the first subseries triplet beginning at λ 3404 in the ratio 3 : 4, and the second subseries triplet beginning at λ 4678 in the ratio 4 : 5; showing the effect of increased capacity to be opposite to that of self-induction, both in general and for the two subseries.

Finally, two photographs were made with the same capacity (four jars), but with very different primary currents. The brightness of the spark was so greatly changed as to require fifteen times as long an exposure with the small current as with

PLATE XXI.



Effects of Varied Conditions on Spark Spectra.

Figs. 1, 2, Cadmium. Figs. 3, 4, Magnesium. Figs. 5–8, Calcium.

the large, for the same average intensity of the spectrum. But little relative change could then be detected between the series and non-series lines, offering a striking contrast to the changes observed when a similar difference in the brightness of the spark was produced by increase of capacity. In this experiment we have a greatly increased vaporization, with probably only slight changes in the oscillations, indicating that the series lines are dependent on the vapor density in the spark rather than upon the electrical conditions; while both this and the results with capacity and self-induction point to the conclusion that the vibrations producing the non-series lines are favored by the peculiar conditions existing in the oscillations.

ZINC.

An exposure five times as long with self-induction as without gave approximately the same intensity for corresponding series lines, but the relative difference between the lines of the first and second subseries was greater than in the case of any other metal studied. Again it is the first subseries which is weakened as compared to the second. If the second subseries triplets beginning at λ 3018 and λ 4680 are brought to nearly the same intensity, the triplets of the first subseries beginning at λ 2757 and λ 3282 are rather less than one-half as strong with self-induction. Comparing the two triplets of the second subseries, the ultraviolet triplet shows the weakening effect of self-induction considerably more than the green triplet.

Turning to the non-series lines, we find λλ 2502, 2558, 4912, 4925 are very much reduced by self-induction, being changed more than any of the series lines. λ 4630 is little changed, while λ 3076 is relatively much strengthened. This action on the non-series lines is directly opposite to that noted by Crew[1] when the rotating zinc arc was surrounded by hydrogen. The effect of hydrogen was to intensify λ 2502 and λ 2558, and to weaken λ 3076. The diffuse spark lines λλ 4912, 4925 are more sensitive to the influence of self-induction than any other of the unrelated lines, and seem to belong entirely to the condensed spark, as

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[1] ASTROPHYSICAL JOURNAL, **12**, 167, 1900.

Professor Crew does not mention them as appearing in the rotating arc.

Effect of varying capacity.—A change of capacity from 0.0018 to 0.0162 microfarad gives a relative difference between the first and second subseries directly opposite to that given by self-induction, and to about the same degree. The non-series lines λλ 3076, 4630 are weakened, and the lines λλ 2502, 2558, 4912, 4925 are strengthened by increased capacity; but the non-series lines are changed less by increased capacity than by self-induction, as compared with the series lines. The four lines last mentioned are enhanced by greater capacity to about the same degree as the triplets of the first subseries; while with self-induction these lines are weakened more than the triplets.

MAGNESIUM.

The spark was produced between pointed metallic electrodes of sufficient thickness to prevent melting. As in the case of cadmium, the electrodes were allowed to become slightly oxidized before a photograph was taken.

Effect of self-induction.—When corresponding lines belonging to the two subseries of Kayser and Runge were brought to approximately the same intensity (five times as long an exposure being required with self-induction as without), a group of lines could be at once selected which were very much reduced by self-induction relatively to the series lines. Considering only the stronger lines, this group consists of λλ 2791, 2796, 2798, 2803, 2916, 2929, 2937, 3892, 3896, 4481. The difference is greatest in the lines λλ 2929, 2937, 4481 (Figs. 3 and 4). The non-series lines λλ 2852, 4168, 4352, 4703 are changed but little by self-induction, except to be rendered sharper. λ 2852 is made blacker and the reversal is narrowed.

The lines of the first and more diffuse subseries are weakened by self-induction more than those of the second; but the change in corresponding lines of each subseries *is greater as the wave-length decreases.* For example, in the first subseries, the triplet at λ 3091 is more reduced than that at λ 3829; and in the second subseries the triplet at λ 3330 is weakened more than the green triplet at λ 5168.

Comparing Crew's[1] results with the rotating magnesium arc in hydrogen with the effect of self-induction on the spark discharges, we see that the three lines λλ 2929, 2937, 4481, which Crew found intensified by hydrogen, are greatly weakened by self-induction, the comparison in each case being with reference to the series lines.

Effect of varying capacity.—Comparing photographs taken with 0.0018 and 0.0162 microfarad capacity, the changes produced by increased capacity are in all respects the reverse of those given by self-induction. The lines most rapidly enhanced by increasing capacity are the three non-series lines λλ 2929, 2937, 4481. The first subseries triplets are strengthened more than those of the second subseries, and again the strengthening is most rapid in the region of shorter wave-length. If the exposures are so timed as to bring the green triplet λ 5168 to the same intensity in both cases, the ultra-violet lines of the same series are nearly twice as strong with large as with small capacity.

The shift of the maximum toward the greater wave-lengths seems to be the most definite evidence we have concerning the temperature change produced by self-induction, and indicates a lowering of the temperature by self-induction, with the reverse effect when capacity is increased, if the law governing the radiation of a solid body holds for a luminous vapor. The experiments of Langenbach[2] indicate that the radiation of gases in Geissler tubes follow this law, the hydrogen series lines of shorter wave-length being relatively intensified by conditions which should increase the temperature.

There has been much discussion concerning the origin of the arc and spark lines of magnesium. Schenck[3] showed that λ 4481 is due to the luminous "streamers" given by the oscillations, and it is the line most changed by self-induction. λλ 2929, 2937 are affected almost as much by altered electrical conditions, while the "arc lines," consisting of the series lines and a few others, apparently have vibrations which depend for their intensification upon the conditions attending increased vapor density. The differences between arc and spark spectra in general seem to rest upon a distinction of this sort.

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[1] *Loc. cit.*

[2] *Annalen der Physik* (4), **10**, 789, 1903.

[3] *Loc cit.*

The appearance in the arc of the distinctively spark lines seems to require abnormal conditions which probably approach those of the spark. The fact that with both magnesium and zinc the lines which Crew found changed by an atmosphere of hydrogen around the rotating arc suffer the greatest change by self-induction, and in an opposite direction, seems to offer additional evidence that the differences between the arc with one terminal rotating and the stationary arc are based on electrical changes caused by the constant interruptions, and not by a difference in temperature or vapor density in the two arcs. This unusual electrical action, as Hartmann[1] has pointed out, may be expected to arise from the rapid variation in circuit conditions given by the interruptions.

As to the action of hydrogen on the rotating arc, it would seem that much of the relative difference observed by Professor Crew might be ascribed to the vastly greater number of interruptions required in an atmosphere of hydrogen to give a photograph comparable to that taken in air. As Crew found the rotating magnesium arc in air to give λ4481 ten times as strong as λ4352, it follows that the reduction of the general intensity by hydrogen, necessitating a longer duration of the electrical conditions which favor λ4481, would result in an increase of the difference between these two lines. Another element to be considered is that if the hydrogen atmosphere decreases the vapor density of the arc, as is probable, then the group of lines which seem to depend upon vapor density, including the series lines and λ4352, would be weakened relatively to the spark lines λλ4481, 2937, 2929, which are favored by the strong electrical action.

If we accept the view generally held that hydrogen reduces the temperature of the arc, and also, as seems probable from my observations, that the temperature of the spark is lowered by self-induction, then the opposite effects of hydrogen and self-induction indicate that the spark lines of magnesium are not lines of high temperature. This agrees with the conclusion drawn by Hartmann[2] from the fact that λ4481 rapidly increases in relative intensity in the arc with very low current, indicating that the line is favored by the highly charged condition of the electrodes when the current is frequently interrupted, rather than dependent on temperature or vapor density.

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[1] ASTROPHYSICAL JOURNAL, 17, 270, 1903.

[2] *Loc cit.*

CALCIUM.

The lines of calcium were found to be very sensitive to changes of circuit conditions. The spark passed between carbon electrodes moistened with strong calcium chloride solution. While this method did not insure a constant quantity of calcium in the spark, the relative differences could be reproduced at will, and were so pronounced that there seemed to be no uncertainty in ascribing them to the variations of self-induction and capacity.

Effect of self-induction.—Photographs favorable for comparison were given by an exposure one and one-half times as long with self-induction as without (Figs. 5 and 6). The lines separate into two groups, one of which is very much weakened by self-induction with respect to the other. This weaker group consists of the three line pairs λλ3159, 3179, 3706, 3737, 3934, 3969, having approximately the same difference in wave-number. Further, these pairs are weakened in quite different degrees. The ratio of intensities, with and without self-induction, of the pair of shortest wave-length is about 1 : 6, that of the next pair 1 : 4, and that of the H and K lines 1 : 2. The effect of self-induction is thus more pronounced as the wave-length decreases, *on lines which are probably related*—a result which again points to the conclusion that self-induction causes a reduction of temperature.

The lines of the second group, which are relatively strengthened by self-induction, include those belonging to the first and second subseries of Kayser and Runge, the strong line λ4227 and the unrelated lines in the region studied (to λ5603). These lines are all strengthened in about the ratio 3 : 1. The calcium-oxide band at about λ5525 also appears much stronger with self-induction. By this is not meant an *absolute* strengthening, as the exposures were so timed as to give an average between the two groups of lines.

Effect of varying capacity.—The two photographs (Figs. 7 and 8), taken with 0.0018 and 0.0027 microfarad, respectively, show the effect of greater capacity to be in all respects opposite to that of self-induction. Comparing the three line pairs, that of shortest wave-length is more enhanced by capacity than either of the other pairs. The unrelated lines, including λ4227, are weaker in the photograph with large capacity in about the ratio 1 : 3, this being the degree to which they were enhanced, in the photograph taken with self-induction, while the change of the line pairs by capacity is by no means as great as that given by self-induction. Self-induction has thus a more pronounced effect, as compared with change of capacity, on the three line pairs than on the lines of the other group; corresponding to the effect noted in the case of zinc.

In classifying the calcium lines, then, the three line pairs must be considered as "spark lines," in the sense that they are favored by the electrical conditions in the spark rather than controlled by vapor density, as the other calcium lines appear to be. My observations of the calcium arc spectrum[1] agree with this view, as it was then shown that the series lines were changed more rapidly than the line pairs, both by the amount of calcium in the arc and by gases which appear to alter the vapor density. Again, Sir William and Lady Huggins[2] observed that when the amount of calcium in the spark is diminished, circuit conditions remaining the same, the line λ4227 becomes weaker much faster than the H and K lines. Further evidence in the same direction is the fact that the line pairs are relatively much stronger in the spark than in the arc.

MERCURY.

The spark passed between the surface of mercury in a dish and a pointed copper terminal above. In this way the spark was maintained of constant length, which is impossible if the upper electrode is of carbon, and only the two strong ultra-violet lines of copper appeared.

The results with self-induction for the most part verify those of Huff.[3] With about ten times as long exposure, with as without self-induction, the series lines were obtained of the same intensity, and little, if any, relative difference appears between the lines of the two subseries. The non-series lines may be divided into three groups: (1) those which are much reduced by self-induction relatively to the series lines, as λλ2848, 3790, 3984; (2) those changed to about the same degree as the series lines, as λλ3022, 4078; and (3) the lines λλ5770, 5790, which are not in the region covered by my photographs, but which Huff found relatively much stronger with self-induction. The line λ2848 is reduced by self-induction more than any other line observed, and Huff noticed a rapid intensification of this line by increased capacity. Unlike the foregoing elements, the ultra-violet mercury lines do not seem to suffer greater changes than those of greater wave-length, which may indicate that the lines of this spectrum have little dependence on temperature.

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[1] ASTROPHYSICAL JOURNAL, 18, 120, 1903.

[2] *Ibid.*, 6, 77, 1897; *Proc. R. S.*, 61, 433, 1897.

[3] *Loc. cit.*

ALUMINIUM.

Effect of self-induction.—In the case of aluminium, we again find the non-series lines greatly weakened by self-induction, as compared with the series lines. An exposure two and one-half times as long with self-induction as without served to bring corresponding series lines to nearly the same intensity. The first subseries line pair λλ3082, 3093 was slightly weakened relatively to the pair λλ3944, 3962 of the second subseries. The weaker pairs did not appear with self-induction. The non-series lines λλ2816, 3587, 3602, 3613, 4480, 4513, 4530 were all much reduced by self induction, traces of these appearing only near the poles, when they were not entirely blotted out.

Effect of varying capacity.—Comparing photographs taken with 0.0018 and with 0.0162 microfarad capacity, we find that the lines reduced by self-induction are in all cases strengthened by larger capacity, relatively to the series lines, and extend farther toward the middle of the spectrum. Also the first subseries pair is enhanced considerably faster by increased capacity than the pair of the second subseries.

RESULTS.

The conclusions from the foregoing work may be briefly summarized as follows:

1. The lines of each of the six metals studied may be divided into two groups.

2. The first group contains the series lines and some others. These lines appear to be dependent on the rate of vaporization of the metal rather than upon changed electrical conditions, and the vibrations which produce them are probably of a simple kind. They are reduced by self-induction and enhanced by capacity, but not more than would be explained by the change in vapor density.

3. The second group contains the lines for which no series relations are known. They are weakened by self-induction and enhanced by capacity much more than the lines of the first group, suggesting that the vibrations are more complex and require a stimulus other than mere vaporization, as many of these lines do not appear in the arc.

4. Self-induction and capacity have an opposite effect upon all lines.

5. Of the two subseries, the first is much more sensitive to all changes.

6. The weakening of the series lines is not in proportion to their strength, but the last members of a series are reduced by self-induction much more than the first members, and a shift of the maximum intensity toward greater wave-lengths is produced.

7. The effect of capacity upon series lines is to shift the maximum intensity toward shorter wave-lengths, giving the greatest enhancement to the last members of a series.

I take pleasure in expressing my hearty thanks to Professor Kayser for his kindly interest and frequent advice during the progress of the work.

BONN,
January 1904.

SECONDARY SPECTRA.

By P. G. Nutting.

SINCE early in the development of spectroscopy[1] it has been known that some of the elementary gases electrically excited give two entirely different spectra. One of these, called by Plücker and Hittorf the *primary* spectrum, usually consists of a large number of broad lines, well distributed over the whole visible and neighboring ultra-violet spectrum. The secondary spectrum, on the other hand, consists usually of but few lines, and these very prominent. It is the spectrum obtained when capacity is connected in parallel with the tube. The two spectra are easily obtained with an ordinary Plücker tube, having not too long nor too fine a capillary, and containing nitrogen, sulphur, or iodine vapor at a pressure of 2–10 mm. With a large condenser in parallel such a tube shows a secondary spectrum; without the condenser it shows the primary spectrum, if the current be not excessive. Some gases which exhibit secondary spectra also show anode and cathode glows having quite different spectra. With mercury vapor, however, the anode and cathode spectra are practically identical, and neither differs greatly from the spectrum obtained when a large condenser is placed in shunt circuit. The present investigation was undertaken to separate, in the Mendeleef system, those elements which show multiple spectra from those that do not, and to determine what conditions govern the production of secondary spectra.

Starting with the seventh group of the periodic system, it was found that chlorine, bromine, and iodine, all of the group that could be worked with, gave multiple spectra. The effect is particularly striking with bromine and iodine. Likewise, all of the sixth group available gave multiple spectra, namely, oxygen, sulphur, selenium, and tellurium. In the fifth group, nitrogen, phosphorus, and arsenic exhibit multiple spectra, while bismuth does not. With arsenic, however, the primary (anode) and secondary spectra have two prominent green lines in common. In the fourth group, only the more metallic elements tin and lead could be used in a Plücker tube. The spectra of these were found not to change on connecting a condenser in shunt. In the third group, aluminium, indium, and thallium; and in the second group, magnesium, zinc, cadmium, and mercury, give only line spectra which are not essentially altered by capacity in parallel. Hydrogen excepted, the first group shows only single spectra. Without taking up the much-discussed[1] question of the rôle of water vapor in gas conduction, from the point of view of multiple spectra the evidence is very strong that the fine-line spectrum of hydrogen is a true primary spectrum, while the four-line spectrum is a true secondary. The latter is relatively enhanced under the same conditions that bring out the secondary spectra of other multiple spectra elements. The primary and secondary spectra of other elements, notably chlorine and bromine, may be made to coexist in the same way, and the presence of water vapor certainly favors the preponderance of the secondary spectra of other elements as well as hydrogen. Oxygen and sulphur are striking examples.

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[1] PLÜCKER and HITTORF, "On the Spectra of Ignited Gases and Vapors, with Special Regard to the Different Spectra of the Same Elementary Gaseous Substance," *Phil. Trans.*, **155**, 1–29, 1865.

In the helium group there are wide differences. Helium itself shows but a single spectrum. Anode and cathode glows give identical spectra, and both remain practically unchanged on the passage of the condenser discharge. Argon, however, shows at least four widely different spectra. The red primary (anode) and blue secondary spectra have been described by several observers.[2] But the cathode glow shows quite a different spectrum from the anode (capillary) glow. With low dispersion it appears nearly continuous in the yellow, green, and blue, while the strong red line and the violet group of the anode glow are lacking. When the blue condenser discharge is produced in the capillary, there is a buff-colored glow in the bulbs at either end. The spectrum of this glow shows the blue group lacking, but the yellow group of the red primary anode spectrum present. This difference between bulb and capillary spectra can hardly be regarded as other than a current density effect, since this is the chief, if not the only, difference in the excitation. As we should expect, the bulb spectrum with condenser is intermediate between the capillary spectrum with condenser and the red capillary spectrum without condenser.

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[1] CALLENDAR, *Nature*, **56**, 624, 1897. TROWBRIDGE, *Phil. Mag.*, (6) **2**, 370, 1901. LEWIS, *Phil. Mag.*, (6) **3**, 512, 1902. PARSONS, ASTROPHYSICAL JOURNAL, **18**, 112, 1903.

[2] TROWBRIDGE and RICHARDS, *Phil. Mag.*, (5) **43**, 77–83, 1897. **KAYSER, *Berlin* *Akad.***, 1896. TRAVERS, *Experimental Study of Gases*, 1901, p. 312.

The tubes of helium and argon for these tests were loaned by Professor Monroe, of Columbia University. Of neon, krypton, and xenon only the spectra of the two latter are said to be seriously affected by the condenser discharge.[1] No differences between anode and cathode capillary and bulb spectra appear to have been recorded.

In the accompanying abridged Mendeleef table the elements showing multiple spectra are separated by different type from those that do not. Elements showing distinct anode and cathode spectra are bracketed.

O		I		II		III		IV		V		VI		VII	
		H													
	He		Li		Be		**B**		**C**		**(N)**		**(O)**		**F**
Ne		Na		Mg		Al		**Si**		**P**		**S**		**(Cl)**	
	(A)		K		Ca		Sc		**Ti**		**V**		**Cr**		—
—		Cu		Zn		Ga		Ge		**As**		**Se**		**Br**	
	Kr		Rb		Sr		Y		Zr		**Nb**		**Mo**		—
--		Ag		Cd		In		Sn		Sb		**Te**		**I**	
	Xe		Cs		Ba		La		Ce		Di		- -		—
—		Au		Hg		Tl		Pb		Bi		—		—	

Excepting then the anomalous helium group and questioning hydrogen, we may say that in general, so far as observations go, *the acid-forming elements have multiple spectra*, while metallic elements do not. Near the dividing line primary and secondary spectra are nearly alike; the primary spectrum is heavily lined, and adding a condenser affects it but slightly.

The heavily banded primary spectra of sulphur and iodine suggest a classification on the basis of monatomic or polyatomic character. And we might expect an atom bound with several others in a molecule to radiate energy of more different periods than a free atom. But the behavior of nitrogen, argon, and xenon contradicts this view, and the behavior of compounds like water and *HgS* vapor strongly indicates that even iodine and sulphur are completely dissociated by the current when they become luminous.

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[1] BALY, *Chem. News*, **88**, 26, 1903.

Why should a condenser discharge produce a secondary spectrum? The oscillation frequency of a condenser is so much less than the frequency of collision of an electron in a gas at 1 mm pressure[1] that an electron must collide a great number of times before the impelling force is reversed. Hence the oscillatory nature of the discharge *per se* could have little effect on the spectrum of a gas. On the other hand, the current density during discharge is thousands of times as great as during the steady flow of the same current. Trowbridge has shown (*loc. cit.*) that an increase in current density alone is sufficient to change the red glow of argon into the blue glow characteristic of the condenser discharge.

In testing other gases for the effect of excessive current density, specially designed Plücker tubes were used. One form had a very fine (thermometer) capillary and hollow cylindrical electrodes; another had a third bulb interposed in the middle of the capillary. In this way the current density could be made a hundred or a thousand times as great in parts of the tubes as in others. Bromine, iodine, and hydrogen easily show the current density effect within the range of current that a common glass tube will carry. The primary spectrum changes continuously over into the secondary spectrum as the current is increased. Nitrogen and the sulphur group failed to show the secondary spectrum with the largest steady currents that glass tubes could carry. Argon is so sensitive to changes in current density that, in conjunction with a pocket spectroscope, it might be used as a milliammeter. Excessive current in a gas means excessive excitation of the radiating particles. If an electric current is a convection of the charged parts of atoms, and luminous and ultra-violet radiation is caused by the vibration of these charged parts within the atom, we have a simple explanation of the effect of excessive current in producing secondary spectra. When the excitation is the feeblest that will produce luminosity, we should have but a single electron torn from an occasional atom by the passage of the current. With increased current, electrons would be torn from a larger percentage of the atoms; we should still have the primary spectrum, but more intense. But with excessively great currents, we should expect, not one, but several electrons to be torn from each atom. The remainder of the atom would have greatly altered modes of vibration, and we should expect the secondary spectrum actually obtained. The free electrons would radiate as moving charges between impacts, and, if impacts were frequent, would seriously interfere with atomic vibrations. Hence an excessive current should produce widening of spectral lines and a faint continuous background. A still further increase in current density in any gas would produce a continuous spectrum, a result already realized by Trowbridge by sending a powerful condenser discharge through hydrogen in a quartz tube.

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[1] DAVIS, *Phys. Rev.*, **17**. 501-505, December 1903.

It is difficult to get beyond mere speculation in connecting multiple spectra with acid-forming or polyatomic character, or with high valency. It appears to be easier to tear electrons from metallic than from non-metallic atoms. For this reason alone it may be possible to excite non-metallic atoms so feebly as to give a primary (whole atom) spectrum, while with metallic vapors we get only a secondary spectrum with the feeblest current that will produce luminosity. Two other significant and quite general properties of primary spectra may be noted. Primary spectra, perhaps without a single exception, become less banded and more strongly lined in character for the shorter wavelengths. Again, primary and secondary spectra differ less in the ultra-violet than in the visible spectral regions. Both of these facts indicate that the more quickly moving electrons have greater freedom of motion within the atom, and that their motion is less interfered with by impact. The most characteristic, definite, and invariant portion of the elementary spectra appears to be that lying between wave-lengths 200 and 350 $\mu\mu$. This portion should prove most useful in identifying elements, just as the infra-red spectra are characteristic of substances and molecular structure in general.

Only a few substances show markedly different spectra in anode and cathode glows. Nitrogen, oxygen, argon, and chlorine are the only ones whose anode and cathode glows are noticeably different in color. Bromine and iodine in Plücker tubes show slight differences, both in general color and spectra, between capillary (anode) and cathode glows; but these differences appear to be due entirely to differences in current density. Not one of the sixteen metallic vapors examined showed any differences either in color or in their spectra, nor do any of the acid-forming elements, aside from the three mentioned. The only general statements we can make regarding these elements that do exhibit differences in anode and cathode spectra are that they all belong to the class of elements showing both primary and secondary spectra, and that they are all of low atomic weight.

The three spectra of nitrogen have been studied in some detail by Lewis.[1] Oxygen presents still more interesting features. Anode and cathode are both line spectra, having but one prominent (red) line in common. The secondary (spark) spectrum is like the anode in the red and yellow, and like the cathode spectrum in the blue and violet. Secondary and anode spectra have four prominent lines in common; secondary and cathode, six. The differences in chlorine are not marked; in argon they appear to be all due chiefly to differences in current density.

It is difficult to account for spectral differences at anode and cathode. To be sure, the excitation is probably quite different in character in the two regions; but why should the atomic modes of vibration be altered even then? If, at the cathode, the atoms of the gas are set in vibration without disruption by the projected negative electrons, the cathode spectrum should resemble the primary. If, on the other hand, there is atomic disruption in the cathode glow, the cathode spectrum should resemble the true secondary, and could be imitated by increasing the current density in the anode glow. Further study of the remarkable multiple spectra of oxygen may throw light on this point.

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[1] ASTROPHYSICAL JOURNAL, 17, 258–269, May 1903.

National Bureau of Standards,
Washington, D. C.
February 1904.

ON A POSSIBLE VARIABLE RADIAL VELOCITY OF LONG PERIOD.

By H. C. LORD.

IN the fall of 1901 a number of spectrograms of η *Piscium* were secured. Four of these were measured at that time, but, for reasons to be given later, were not reduced until a few months ago. These four plates gave as the mean velocity +21.9km per second. Upon reobserving the star this fall, I was surprised to find that the first plate secured, No. 827, gave a velocity of only +13.7km per second. Thinking that this might be due to a bad plate—for No. 827 was badly underexposed—I secured five more spectrograms, which gave as a mean for 1904 +12.3km per second. This variation, if real, is one of considerable interest, and I take this opportunity to bring this star especially to the notice of those engaged in the measurement of motion in the line of sight.

In view of the importance of the subject, I shall give a more complete history of these observations than would ordinarily be done. After several years' experience with the battery of two dense 60 prisms in photographing stellar spectra for motion in the line of sight, I was led to believe that better results could be secured with three light flint prisms, carefully designed. After a number of preliminary experiments, such a battery of three prisms was added to our equipment. The optical work was by Brashear, and the mechanical work, owing to a lack of funds, I was obliged to do myself. The three prisms are fixed in the position of minimum deviation for $H\gamma$. The collimator beam is 25mm in diameter. The prisms increase in size so as to transmit a clear beam of 30mm diameter between wave-length limits of 4600 and 4100 approximately. The prism angles are 62°54′ and the index of refraction for $H\gamma$ is about 1.64. The camera has a focal length of about 380mm. The linear dispersion on the photographic plates is such that one one-thousandth of a millimeter corresponds to a velocity of 1.4km per second at $H\gamma$.

The performance of these prisms is most satisfactory. In order to test them, the star *η Piscium* was selected as being as faint as I could hope to get, its photographic magnitude as given in the *Draper Catalogue* being only 5.02. The diameter of the objective of the equatorial at this observatory is only 12.5 inches, and we are located within the limits of a city of 150,000 population where soft coal is used extensively. Satisfactory spectrograms were secured in sixty minutes, although exposures of from seventy-five to ninety minutes were generally given.

This equipment was finished in the fall of 1901, and four spectrograms of *η Piscium* were secured and measured, but not reduced, as a slight source of error was detected in the hydrogen comparison spectrum; but as both hydrogen and iron were used, no appreciable error could have been introduced in the resulting velocities, as is completely proved by observations made on other stars taken after this error had been eliminated. Much time was then spent in devising a scheme whereby the measures of such plates could be easily, rapidly, and rigorously reduced by the method of least squares. This method I hope to give in detail at another time; suffice it to say that all plates are measured with violet end left and violet end right, and the measurements separately reduced by the method of least squares.

By the spring of 1902 the work was nicely started, when it was again interrupted for nearly a year by the addition to the observatory of a large amount of apparatus, including several buildings, for purposes of instruction. During this time Mr. B. F. Maag came to this observatory as assistant, and as soon as he was satisfactorily trained, all the work of measuring and reducing the plates was intrusted to him. In every case, however, the photographs were taken by myself. A considerable number of duplicate measures of the same plates made both by Mr. Maag and myself show practically no systematic differences.

Work was again started during the summer of 1903, and in getting up back work the old measures of *η Piscium* were reduced with the following results:

Date	Plate No.	Velocity Reduced to Sun	Measured by
1902			
Jan. 1........	672	+20.0	Lord
4........	674	+20.7	Lord
6........	677	+21.1	Lord
10........	679	+25.4	Lord

The mean of these results gives +21.9km per second.

In order to have five separate determinations on each star, I undertook to reobserve *η Piscium* this fall. Great difficulty was encountered in getting a good plate. Twelve ninety-minute exposures were made before one, even though badly underexposed, was deemed suitable for measurement. I attributed this trouble first to the sky, then to the plates; but the chief cause of trouble was not discovered until after Plate 827 had been taken. It was then found that, for some unexplained reason, the focus of the large objective for *Hγ* had changed by about 2mm. This was corrected; and from that time on, with new plates, not a single exposure was lost when the sky was even in a fair condition.

Plate 827 gave a velocity of +13.7km per second—a change of about 8km per second from those two years earlier. It was seen at once that more work was needed. Mr. Maag then remeasured Plate 679, with a result of +24.5, as against +25.4 measured by Lord. An old plate, No. 662, taken December 15, 1901, was hunted up and measured by Mr. Maag, with a result of +18.5km per second, making the mean for that year +21.1.

The following additional plates were secured:

Date	Plate No.	Velocity Reduced to Sun	Measured by
1903			
Dec. 7.......	831	+17.0	Maag
13.......	835	+10.6	Maag
15.......	837	+ 9.4	Maag
22.......	841	+12.7	Maag
1904			
Jan. 9......	842	+10.6	Maag

After this date the star was too near the Sun for observation. The above results, together with Plate 827, give as the present velocity of this star +12.3 km per second—a change of 8.8 km per second in two years. Collecting these results, we have:

1901 and 1902: mean velocity, +21.1; maximum measurement, +25.4; minimum measurement, +18.5.

1903 and 1904: mean velocity, +12.3; maximum measurement, +17.0; minimum measurement, +9.4.

Plate 662 was probably not measured in 1901, as I am under the impression that the diaphragm which covers the more intense comparison lines during the greater part of the exposure was not then in place. The variation *inter se* of these measures is somewhat large, but not excessive, I think, in view of the instrumental power at my command. They are, however, larger than we get ordinarily. This may be due, however, to the low magnitude of *η Piscium.*

The exposures never exceeded ninety minutes.

I give below a complete table of results:

Plate No.	Date of Photograph	Observed Velocity			Reduct. to Sun	Vel. Red. to Sun	No. Lines V. L.	No. Lines V. R.	Measured by
		V. L.	V. R.	Mean					
662	Dec. 15, 1901	+45.1	+42.9	+44.0	−25.5	+18.5	14	14	Maag
672	Jan. 1, 1902	+50.3	+47.6	+49.0	−29.0	+20.0	23	23	Lord
674	4,	+52.8	+47.4	+50.1	−29.4	+20.7	20	20	Lord
677	6,	+52.5	+48.7	+50.6	−29.5	+21.1	14	15	Lord
679	10,	+56.1	+54.3	+55.2	29.8	+25.4	18	17	Lord
679	Second measure	+54.6	+53.9	+54.2	29.8	+24.4	12	12	Maag
827	Nov. 26, 1903	+35.1	+29.7	+32.4	−18.7	+13.7	13	13	Maag
831	Dec. 7,	+40.1	+39.4	+39.8	−22.8	+17.0	13	13	Maag
835	13,	+35.6	+35.0	+35.3	−24.7	+10.6	18	18	Maag
837	15,	+36.4	+33.1	+34.8	−25.3	+ 9.5	13	13	Maag
841	22,	+41.1	+38.4	+39.8	27.0	+12.8	12	12	Maag
842	Jan. 9, 1904	+42.1	+38.7	+40.4	−29.8	+10.6	12	12	Maag

In all cases *Hγ* and thirteen carefully selected iron lines are used for comparison.

That the above observations represent a real change in velocity, and are not simply errors of observation, I am led to believe from the following considerations:

1. The spectrum of *η Piscium* is well suited to spectroscopic measurement, containing many well-defined solar lines, being classed as Type XIV*a* by Miss Maury.

2. Observations of *Venus* in 1902 gave as the mean of ten residuals, seven taken just after sunset and three just before sunrise, in the sense C.—O., −2 km per second.

3. The close agreement of the work done here with that of other observers, as the following table will show:

Star	Campbell	Wright	Vogel	Scheiner	Frost and Adams	Lord
α *Cassiopeiae*....	− 4.3	......	−14.9	−15.6	......	− 0.6 in 1897 − 2.6 in 1903 − 0.4 in 1898
α *Arietis*	−14.1	......	−14.5	−14.9	−13.7	−12.5 Oct. 1903
ε *Pegasi*........	+ 5.7	......	+ 7.3	+ 8.6	+ 6.1	+ 6.2 Sept. and Oct. 1903
ε *Leonis*........	......	+5.1	......	......	+ 5.5	+ 7.8 Mar. and Apr. 1898
α *Ursae Majoris*.	− 9.8	......	−10.3	−12.7	......	− 5.4 Apr. 1902
α *Boötis*........	......	......	− 7.0	− 8.3	− 4.8	− 4.0 " 1902
ι *Aurigae*	......	......	......	......	+19.0	+20.8 Feb. 1898

In addition to the above, two plates of *η Boötis* taken in 1899 gave a mean of +13.0 km, and five taken in 1902 gave a mean of +12.0 km per second. Furthermore, of two plates of *δ Cephei*, one taken August 24, 1903, gave −22.7 km, and one taken August 25, 1903, gave −6.0 km per second, though at that time neither Mr. Maag nor myself knew it was a spectroscopic double.

The data of the above table in the case of Campbell, Wright, and Frost and Adams are taken from papers published in the ASTROPHYSICAL JOURNAL; in the case of Vogel and Scheiner, from Frost's Scheiner's *Astronomical Spectroscopy*.

In conclusion, I wish to acknowledge my indebtedness to my assistant, Mr. Maag, whose care and enthusiasm in the laborious work of measuring and reducing the plates have contributed much to the value of these observations.

EMERSON MCMILLIN OBSERVATORY,
Columbus, Ohio,
February 9, 1904.

ON THE INVARIABILITY OF THE WAVE-LENGTHS IN THE SPARK AND ARC SPECTRUM OF ZINC.[1]

By J. M. EDER and E. VALENTA.

THE width of the lines in the arc and spark spectrum is a complicated and, at present, little-understood function of the temperature, pressure, and density of the luminous vapor (H. Kayser[2]), and is probably dependent on the nature of the electrical stimulus and the dielectric (Hartmann[3]). The experimental observations of the phenomena of the broadening of the lines have so far by no means reached a final conclusion. In particular, the question is undecided whether or not the maximum of intensity—in a sense the center of gravity of a line—is displaced as the line broadens, a question of fundamental significance for all branches of spectroscopy.

Humphreys and Mohler[4] have demonstrated beyond doubt that actual displacements of spectral lines, as clearly evident changes of wave-length occur as a result of variations of external pressure. F. Exner and E. Haschek, however, went decidedly farther, and stated that these displacements occur more strongly in the spark than in the arc, and depend not only on the external atmospheric pressure, but also on the partial density of the vapor concerned.[5] They stated further that many spark spectra exhibit considerable shifts of lines as compared with the same lines in the arc (in both cases at ordinary external atmospheric pressure[1]), attempting to explain it by pressure effects in the spark, and they tried to calculate the pressure in the spark from the amount of these displacements. Haschek and Mache[2] sought to demonstrate directly the pressure in the spark, but obtained no agreement between the observed values and those computed from the "displacements." Later Haschek concluded from his further experiments[3] that different laws hold for displacements in the arc from those in the spark, so that it is not permissible to compute the pressure in the spark from the displacements of the lines. The pressures observed by Haschek accord so badly with the computed values that he himself says: "The computed pressures are so greatly different from each other that it cannot be doubted that the displacements of the lines are determined by other causes." He suggests as such another cause of the "shifts" "the increasing density of the luminous vapor;" with equal increase of vapor density the displacement is supposed "to be greater for the spark than for the arc lines." Thus, for instance, the zinc lines at λλ 3282, 3302, 4680, 4722 are said by Haschek to have a wave-length greater by from 0.03 to 0.16 tenth-meters in the spark than in the arc. In other cases Haschek cites shifts of as much as 0.2 tenth-meter for spectra with many lines, and up to 0.07 tenth-meter for spectra with few lines. These are very considerable quantities, and far beyond the allowable limits of error for grating spectra. As evidence of the correctness of these observations he adduces numerous measures of wave-lengths (with different elements, as *Al, Zn, Ca, Si, Zr, Cr, Ti, Ce, Va*, etc.).[4] These data gave the impression that the existence of relative shifts between spark and arc lines at ordinary atmospheric pressures was certainly established. According to Haschek, the quantity of vapor had a demonstrable effect on the actual wave-length of lines, so that in his opinion *a method of quantitative spectrum analysis could be based on the measurement of these so-called*

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[1] Translated from the *Sitzungsberichte der K. Akad. der Wiss. in Wien*, Math.-Naturw. Klasse, **112**, II*a*. Communicated at the session of October 22, 1903.

[2] *Handbuch der Spectroscopie*, **2**, 296, 1902.

[3] *Sitzungsber. der K. Akad. der Wiss. zu Berlin*, 1903, 40 and 234.

[4] ASTROPHYSICAL JOURNAL, 1896 and 1897. They raised to several atmospheres the pressure of the gas within which the arc was produced, and observed the displacement of the different spectral lines toward the red, and thus found that the increase in wave-length is proportional to the pressure of the surrounding gas.

[5] EXNER and HASCHEK, *Wellenlängentabellen für Spektralanalytische Untersuchungen*, Leipzig and Wien, 1902, p. 13.

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[1] No reference is made in this paper to displacements of lines caused by a rapid motion of the source of light in the line of sight according to Doppler's principle, which is used for measuring the radial velocities of stars.

[2] *Sitzungsberichte, Wien*, 1898.

[3] *Ibid.*, 110, II*a*, 181, March 1901.

[4] Meanwhile N. A. Kent demonstrated that for titanium lines Haschek's shifts of 0.13 tenth-meter do not occur. ASTROPHYSICAL JOURNAL, 17, 286, 1903.

shifts of lines.[1] For instance, the wave-length 4722.510 was held to be accurate for pure zinc (spark spectrum), while for a 5 per cent. zinc alloy used as electrode the wave-length was only 4722.399. Thus the partial density in the luminous vapor would be of decisive influence on the wave-length.

The doctrine of the dependence of the wave-length of the spectral lines upon the partial density of the vapor under examination is given a position of prime importance in the work by Exner and Haschek entitled *Wellenlängentabellen für spektralanalytische Untersuchungen auf Grund der ultravioletten Funkenspektren der Elemente* (Leipzig and Wien, 1902, Teil I, p. 13). We might well concede to the extensive numerical data they offer as the result of their measures of wave-lengths an indisputable weight of evidence, if we were able to suppress our well-founded suspicion of the value of their photographic material as evidence.

In case of the spark spectra of calcium and lithium, we obtained on an earlier occasion results not in accord with the statements cited, as we then accurately demonstrated (pointing out that errors of a photographic nature doubtless were involved);[2] and when we recently began measurements on the spectrum of zinc, we again met with experimental results contradictory to the statements of Haschek. Similarly, our findings as to the spectra of alloys with large and small proportions of zinc contradict the statements and measures of Haschek.

Objections to the statements of Exner and Haschek were also made by H. Kayser,[3] of Bonn, who had never observed an effect of the quantity of the element present on the wave-length in his investigations of arc spectra. In his opinion, the partial pressure of the vapor in the arc produces no shifts, as may be readily demonstrated if apparatus of high resolving power is employed, but otherwise apparent shifts may occur. As to the relation between spark and arc wave-lengths and the effect of the partial pressure on shifts in the spark spectrum, no experimental confirmation has so far appeared from other sources for the assumed shifts of Exner and Haschek.

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[1] *Sitzungberichte, Wien*, **111**, II*a*, 232, February 1902.

[2] "Ueber das Funkenspektrum des Calciums und Lithiums und seine Verbreitterungs- und Umkehrungserscheinungen." *Denkschriften der Akad. der Wiss. Wien*, **67**, 1898.

[3] *Handbuch der Spektroscopie*, **2**, 297, 308, 309, 310.

It must be expressly remarked here that the question involved is not that of the breadth of the lines in the so-called unsymmetrical broadening, which has been known for years, and which is exhibited, among other ways, when the lines from pure metallic electrodes (as zinc, lead, etc.) are strongly widened toward the red in the spark with large capacity, while they become quite sharp if the metals are present in the vapor as small impurities of the electrodes (hence with slight partial pressure). We are, on the contrary, in this displacement phenomenon of Exner and Haschek concerned with the precise wave-length of the maximum of intensity of the lines, which in a sense represents the center of gravity of the lines.

If we base such measurements upon the maximum of intensity of the lines in question, which at present is the only admissible and generally adopted procedure, as was also recognized by Haschek,[1] we arrive at results contradictory to the statements of Haschek when the photographic work is done correctly and the proper degree of resolution is employed for the spectra.

We first selected the spark and arc spectra of zinc, and occupied ourselves for a long time exclusively with eight zinc lines which might be regarded as typical, and which were brought forward by Haschek, along with other similar spectra, as furnishing especially strong evidence in support of his theory.

Our large Rowland concave grating of fifteen feet radius[2] is an excellent one, and was pronounced by H. Kayser, of Bonn, who saw our spectrum photographs, to be of the very highest grade. Now, the possibility of surely finding the maximum of intensity of unsymmetrically broadened lines—and Haschek's investigations deal with these alone—depends upon limiting as much as is practicable the extent of the broadened and diffuse portions of the lines by careful photographic procedure. We worked with a slit having sharp steel jaws at a width of from 0.008 to 0.03 mm, and obtained a good degree of sharpness of the lines at the latter width. We determined the true photographic focus of the grating by empirical settings at each half-millimeter,[1] and bent the photographic plate (on mirror glass) to the focal curve of the grating. We effected the superposition of the lines by means of a light diaphragm which could be moved up and down in front of the plate-holder; by the motion of the diaphragm each line could be photographed in three parts, one after another. At every exposure the whole grating was fully illuminated. The exposures were short.

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[1] *Sitzungsberichte, Wien*, 111, II*a*, 232, 1902.

[2] That is, of the same radius as the grating employed by Exner and Haschek.

Agreement has hitherto been lacking as to what constitutes a "short exposure" or "minimum exposure" with the best degree of sharpness and delicacy and with correct development. Until such agreement is secured, differences in observations of the so-called shifts of the spectral lines will occur—as have been repeatedly described by Haschek in contradiction to other spectroscopists—and self-deceptions will be difficult to control. In order to give some definite data as to the sharpness of lines, the observer should not only specify the width in tenth-meters of the lines measured, but should also state the degree of "blackening" for questionable lines on the particular negative, which blackening should be quite slight. It might, indeed, be made a criterion as to whether a photograph answers the most rigorous requirements if an unsymmetrically broadened line was obtained with a certain minimum width for an average or for a most delicate degree of blackening. We measured the width of the sharp iron lines of the arc, obtained with a favorable arrangement of the apparatus, and found they were from 0.03 to 0.04 mm wide, with a slit-width of 0.03 mm (for minimum exposure), and had a blackening of from 0.5 to 1.0, according to measurement with a Hartmann microphotometer. The broadening of strongly affected zinc lines under just the same conditions was never less than 0.06 mm on the negatives. Reduced to tenth-meters, the zinc line at λ4810 for instance had in the arc a width of 0.07, against 0.19 in the spark (both with minimum exposure). The coincidence of the two lines at the point of their maximum intensity could nevertheless be readily demonstrated. If the spark was exposed twice as long, however, the unsymmetrical broadening is so great that the total width of the line amounted to from 0.53 to 0.71 t.-m., when it was difficult to find the maximum of intensity: the nucleus of the line runs toward the red, but the observer may still believe that he is setting on the maximum, and then readily finds an apparent shift of 0.008 t.-m., which rises to 0.02, and may become still larger with longer exposures, poor development, and defective settings due to deficiency of light. The cause of this pseudo-shift is to be sought in the fact that the nucleus of the line is no longer resolved. The focusing also has an effect not to be underestimated, for with a slightly inaccurate focus unsymmetrically broadened lines run out so as to be unrecognizable.

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[1] On such spectrum photographs, where the sharpest definition is demanded, a change of 1 mm in the setting makes very marked changes on the plate, even with a total focal length of six meters.

It is hard to decide whether this explanation of the highly contradictory statements of different spectroscopists who are photographing one and the same phenomenon is sufficient for all cases, but it is a fact that by carefully performing the spectrographic processes in the manner indicated we have been able to prove that all the alleged phenomena of shifts, described by Haschek for zinc, among other metals, *do not exist.*

Our experimental arrangements for producing the spark discharges between zinc electrodes followed strictly those conditions under which Haschek believed that he found "shifts." He states expressly in his "Spektralanalytischen Studien"[1] that the lines are more strongly shifted with a Ruhmkorff coil and hammer interrupter than with such a coil and a Wehnelt interrupter, or than with a transformer. We therefore also employed powerful induction coils with hammer interrupters, and indeed coils with a sparking distance of from 12 to 25 cm, having a corresponding battery of condensers, so that without doubt any real shift could not have escaped us.

Under these conditions, however, powerful effects of unsymmetrical broadening appear for the zinc lines at λλ 4680, 4722, and 4810, and we then had before us one of the phenomena described as shifts by Exner and Haschek. Our heliogravure[1] shows two zinc spectra photographed precisely over one another, which clearly show the appearance of the "shift-phenomenon." In fact, on a superficial examination one would be disposed to speak here of a displacement of the lines, although a shift of the true maxima of intensity is actually not present. Similar erroneous "displacement phenomena" arise with various other experimental arrangements. This appearance is presented by overexposed photographs of zinc lines when one electrode of pure zinc is used, while the other is an alloy containing little zinc, which was regarded by Exner and Haschek as an effect of the partial pressure of the vapor. With defective definition of the spectra the comparison plates of zinc lines in the arc (narrow lines) and in the spark (unsymmetrically broadened) show a similar appearance. We remark, however, that the two spectra in our figure were obtained with one and the same zinc spark with a short and a long exposure (one-half minute as compared with five minutes), and that the spurious shift is only the photographic expression of the unsymmetrical broadening—just as the photography of a band of light with wedge-shaped shading always shows on prolonged exposure, even when the maxima of intensity are kept perfectly constant. Very short exposures bring out only the maxima of intensity, which coincide, while with long exposure the spark lines are more widened toward the red side than toward the side of shorter wave-lengths, and with somewhat longer development of the plate the maximum of intensity of the line blends with the unsymmetrical broadening. Having now discussed the conditions under which the phenomenon in question occurs, we can proceed to a description of the results of our own experiments, in which we carefully avoided all conditions which might be regarded as sources of error. With the accurate observance of the minimum exposures, with correct development of the plates, and with best definition of the spectra, it appeared (1) that at ordinary atmospheric pressure there exist no relative shifts between the arc and spark spectra, as were said by Exner and Haschek to occur; (2) that there also exist no shifts in the spark spectrum which could be attributed to a reduced quantity of the element present in the vapor; that is, that a dependence on the partial pressure as assumed by Exner and Haschek cannot be proven.

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[1] *Sitzungsberichte, Wien*, 110, II*a*, 200, 1901.

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[1] Not reproduced here.—Eds.

In both cases there occur only the well-known variable, unsymmetrical broadenings, but the intensity-maxima of the lines coincide perfectly in our experiments.

We studied the same zinc lines for which Haschek observed shifts in the spark spectrum, and we first determined their wave-lengths as accurately as was practicable, using Rowland's standards as corrected by Kayser.[1] The lines were measured under the microscope, each line at least ten times each on different photographs, so that an accuracy of 0.002 t.-m. is reached in our wave-length.

Since the lines in the arc spectrum of zinc indicate the normal wave-lengths according to Haschek, and in his view are better adapted for determining the normal wave-length, at slight partial pressure (without fear of the alleged shift phenomena causing disturbance), we selected for producing the zinc arc small electrodes of brass wire, the composition of which was indicated by a chemical analysis to be 36.9 per cent. zinc and 63.1 per cent. copper.

The wave-lengths of the zinc lines in such a small arc between brass electrodes were determined with great care, as follows:

Third order	λ 3302.715
"	3303.068
"	3345.141
"	3345.698
"	3282.451
Second order	4680.327
"	4722.333
"	4810.719

In the same field of view with these were the copper lines of the third order at λλ 3247.671 and 3274.090 (Rowland), which always appear reversed in the arc (symmetrically widened), while the arc spectrum of the iron photographed on the plate for giving standard lines contained a trace of copper, and yielded a fine black *Cu* line which coincided perfectly with the reversal.[1]

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[1] "Normale aus dem Bogenspektrum des Eisens," *Ann. der Phys.*, 3, 195, 1900.

Our heliogravure shows accurately a photograph of the arc spectrum of a zinc-copper alloy. It indicates how with increasing exposure all the lines of the arc spectrum remain quite sharp and broaden symmetrically. With increasing exposure pure zinc in the spark spectrum gives the lines λλ 4680, 4722, 4810 strongly broadened toward the red, but with accurate minimum exposure the brightest part of the line appears sufficiently sharp, in the strongest spark with condensers, for determining its wave-length accurately, and for establishing under the microscope the coincidence of the arc line, as may be seen on our plate. We similarly always found a perfect coincidence in the arc and spark for the zinc lines λλ 3282, 3302, and 3345.1; the spark lines of zinc at λλ 3345.1 and 3302.7 reverse very easily, and then coincide fully with the (unreversed) arc line. A broadening of this line toward the ultra-violet occurs with overexposure. The zinc lines at λλ 3345.698 and 3303.068, which can always be readily obtained as sharp and fine both in the arc and spark, are cited by Haschek himself as not subject to shift, because their tendency to remain sharp even for inaccurate exposure times prevents the illusions which may occur with defective definition for the unsymmetrically broadened lines of zinc at λλ 4680, 4722, etc.

The illustration shows the beautifully accurate coincidence of the reversed arc lines of copper at λλ 3347 and 3274 with the unreversed spark lines. The zinc lines at λλ 4722 and 4810 are somewhat strongly exposed and developed for a strong degree of blackening. Hence the arc lines of the central spectrum are broadened pretty uniformly on both sides, while the spark lines show unsymmetrical broadening and the beginning of a spurious shift, which disappears with a minimum exposure and shorter development, making apparent the perfect coincidence of the lines. The illustration further shows that the zinc lines at λλ3345 and 3302 are in no wise displaced toward the side of greater wave-length, as Haschek erroneously states. This can be seen much more distinctly on measuring the original negative under the microscope.

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[1] In accordance with these experiments of ours, Exner and Haschek also cite the two copper lines at λλ 3247 and 3274 as not subject to displacement in their *Wellenlängentabellen*, I, p. 21.

The suspicion that Haschek had imperfect definition in his spectra gains in probability by the fact that he failed to detect the finer structure of some of the zinc spark lines, which is quite remarkable. While he did not fail to notice the very strong unsymmetrical broadening toward the red of the zinc lines at λλ4680, 4722, and 4810, he did not observe that the zinc lines at λλ 3345.1 and 3302.7 exhibit a tendency to broaden slightly toward the side of the shorter wave-lengths, thus canceling the tendency toward an apparent "shift" toward the red. Nevertheless, Haschek finds these lines strongly shifted in the spark toward the red as compared with the arc, and we find, on the contrary, that with a correct short exposure there is no displacement whatever, but rather a coincidence.

After we had been unable to confirm the statements cited as to the relative shift between arc and spark lines, it remained to carry out further experiments on the effect of a partial pressure of the luminous zinc vapor on the "shift" of the lines. To this end we accurately investigated the spark spectrum of pure zinc and that of alloys of 1 per cent. zinc + 99 per cent. lead, and of 50 per cent. zinc + 50 per cent. lead, as well as alloys of 36.9 per cent. zinc + 63.1 per cent. copper. In accordance with the long since published, generally known, and never questioned experiences of all spectroscopists (and it holds good for all spectra, particularly in the case of unsymmetrically broadened lines), all the lines remain quite sharp even with the increased exposures for alloys containing *little* zinc; while for alloys containing ***much*** zinc they do, indeed, exhibit a strong tendency toward unsymmetrical broadening; and in so far the effect of a partial pressure on the width of the spectral lines unquestionably makes itself felt.

Hence with increasing exposures the effects of unsymmetrical broadening do not proceed in a parallel manner for alloys with a small and with a large proportion of zinc. If measurements are therefore made on strongly exposed plates of such contrasted alloys, by setting on the middle of the ill-defined lines, apparent shifts will appear with increase of partial pressure, but they can be recognized instantly as pseudo-shifts on reverting to minimum exposures and on employing the best-defined spectra. An alloy of 1 per cent. of zinc to 99 per cent. of lead of course gives the separate zinc lines in the spark less bright than from an alloy containing more zinc. A preliminary trial with our strongest sparks (Ruhmkorff coil and jars) indicated that the low percentage alloy must receive an exposure of about 15 minutes as against 30 seconds for the 50 per cent. alloy, in order to obtain the lines at λλ 4680, 4722, and 4810 of approximately equal intensity on the plate. Accordingly, in this preliminary experiment the zinc lines were about thirty times brighter in the first case than in the second.

If we now employ an equivalent exposure time for the two cases, approximating the minimum exposures, which will give lines faint, but just measurable on the spectrogram, we find the wave-lengths of the zinc lines at λλ4680.327, 4722.333, and 4810.719 to be precisely the same in the spark spectrum with 1 per cent., 4 per cent., and 50 per cent. alloys and with pure zinc, and we were never able to observe even in the strongest spark from the jars the "shift" of Exner and Mache or of Haschek.

Haschek[1] states that alloys of 4 per cent. zinc give a wave-length of 4722.399; of 50 per cent. zinc, 4722.434; which would be a very considerable shift toward the red with increasing partial pressure. He found the line at λ 4680 too faint to be measurable in 4 per cent. alloy. This line, however, can be obtained sufficiently strong to be measurable with even a 1 per cent. alloy, if the exposure is correct (as is clearly shown in our illustration). It is evident that Haschek underexposed the low percentage alloy, and overexposed the other, and was deceived as a result of unsymmetrical broadening of the lines with poor definition of his spectra. So far as we can see, Haschek bases his theory of shifts solely on unsymmetrically broadened lines; for the sharp lines not even a pseudo-shift can be observed in the spark as compared with the arc spectrum.

[1] *Sitzungsberichte, Wien*, 111, II*a*, 238 and 240, 1902.

Our results accordingly are: (1) No displacements of meas urable magnitude occur in the spark spectrum of zinc as compared with the lines of the arc. (2) The quantity of the element present, or the partial pressure of its vapor, produces no displacement of the lines of the spark spectrum, and hence Haschek's system of quantitative spectrum analysis falls to the ground. *Per contra*, our observations establish the more certainly those principles (displacements of the lines due to motion in the line of sight according to Doppler's principle, etc.), which presuppose the constancy of the spectral lines, upon which doubt was cast by Haschek's conclusions.

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PRELIMINARY MEASUREMENT OF THE SHORT WAVE-LENGTHS DISCOVERED BY SCHUMANN.[1]

By THEODORE LYMAN.

THE work of Dr. Victor Schumann[2] on the extension of the spectrum beyond λ 1854 is too well known to need discussion. Dr. Schumann estimated the region of his extreme wave-lengths at 1000 Ångström units by an extension of the Helmholtz-Ketteler formula for fluorite, but up to the present time, as far as the author is aware, no direct measurements have been made.

It is now several years since the author first undertook the problem of making such measurements, but it is only very recently that his efforts have met with success. The apparatus used may be briefly described as follows: A concave diffraction grating of 97 cm radius, ruled on speculum metal with 15,028 lines to the inch, was mounted at one end of a brass frame, the other end of which carried the plate-holder and slits. The plate-holder itself was mounted in ways, and its position was controlled by a magnetic device of such a nature that seven exposures could be taken without removing the holder from the mounting. In the use of two slits the plan already described by the author[3] was followed. The illumination of the one slit allowed the spectrum under examination to fall upon the plate, while the illumination of the other caused a standard spectrum to fall upon the first. The shift of one spectrum with respect to the other is dependent on the distance between the slits, and was determined by comparison of the positions of known lines in each spectrum.

The angle of the grating was so adjusted that the part of the spectrum under investigation fell between the two slits, and the photographic plate, 4½ by 2½ cm, was therefore placed in this position. The centers of slits, spectrum, and grating surface lay

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[1] Investigation carried on by grant from the Bache fund.

[2] *Smithsonian Contributions to Knowledge*, No. 1413.

[3] *Physical Review*, **16**, 261, 1903.

in one plane. The whole apparatus, held in adjustment by the frame, was slipped into a drawn-brass tube 110 cm long by 10.5 cm in diameter. The tube was closed permanently at one end, save for an outlet pipe, and was provided at the other with a flange, to fit which a circular brass plate was accurately ground. This plate was pierced by two windows covered, in the earlier experiments, by pieces of fluorite and corresponding in position to the slits of the spectroscope. A "Geryk" vacuum pump served to exhaust the apparatus. The pressures were read by a McLeod gauge.

In all the work the special photographic plates made according to the method described by Schumann[1] were used.

In the earlier work an "end-on" tube filled with hydrogen and closed by a fluorite window was pressed directly against the fluorite window of the apparatus. The pressure in the spectroscope was reduced to 0.08 mm of mercury; thus the light from the hydrogen passed through two plates of fluorite each 2 mm thick and through a column of air about two meters in length at a pressure of 0.08 mm of mercury. The line of shortest wavelength thus obtained had a value 1792 in Ångström units.

In order to eliminate the possible effect of the fluorite, an end-on tube without a window was sealed directly on to the brass plate, and the whole apparatus—spectroscope and discharge tube—was filled with pure, dry hydrogen. Thus the path of the light from the end-on tube to the photographic plate lay entirely in hydrogen. The discharge tube was excited by a transformer run from a 60 cycle alternating circuit and giving a potential difference of 3,000 volts in the secondary. A capacity of about 0.005 microfarads was placed in parallel with the tube.

With this arrangement, with an exposure of five minutes and with a pressure of 2 mm of mercury in the apparatus, a spectrum was obtained showing numerous sharp, strong lines, characterized by the following peculiarities: From the region of λ 1854 to that of λ 1700 the spectrum seems almost continuous, but contains some few faint lines. Near λ 1700 occurs an absorption band whose width seems to depend on the purity of the hydrogen in the apparatus. From λ 1650 the spectrum consists of numerous fine lines, 134 of which have been measured. The most refrangible of these yet observed has a wave-length of 1033. Owing to the dimensions of the plate, only a region of about 760 tenth-meters can be photographed at one time. Thus in the first experiments, where the line at the less refrangible end of the plate had the value λ 1935.2, the limit of short wave-lengths was λ 1178. In order to study the region of still shorter wave-length, it was necessary to turn the grating.

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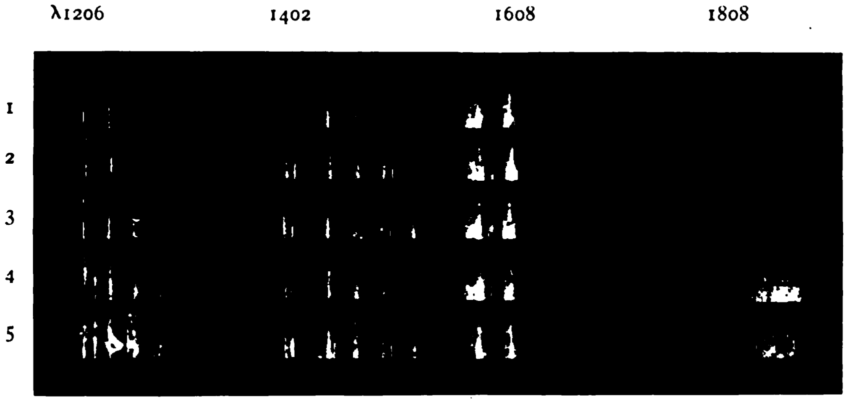
[1] *Annalen der Physik*, 5, 349, 1901.



LINES IN EXTREME ULTRA-VIOLET.

(The defects are on the original negative, and are due to the great difficulty of preparing the Schumann ultra-violet plates.)

The wave-lengths of the lines in the region between λ 1854 and λ 1178 have been carefully determined; but the values beyond this point are only approximate. The error in the region below λ 1178 probably does not exceed one unit. In the values given for the five lines above λ 1178 there may be an error of three units. The strongest line is given the intensity 10.

The plate which accompanies this article shows a twofold enlargement of the spectrum between wave-lengths 1200 and 1880. The spectra, numbered 1, 2, 3, 4, and 5, illustrate the effect which the purity of the hydrogen in the spectroscope seems to have upon the extent of the absorption band near

Wave-Length in Vacuum	Intensity	Wave-Length in Vacuum	Intensity	Wave-Length in Vacuum	Intensity
1033	1	1387.6	1	1541.4	5
1046	1	1393.8	5	1544.1	9
1105	3	1396.0	5	1546.7	9
1118	1	1397.6	1	1550.0	6
1145	1	1402.4	7	1552.9	6
1162	5	1410.1	1	1565.1	6
1178.1	1	1412.5	1	1567.0	6
1180.4	4	1427.3	3	1568.9	6
1182.7	1	1429.6	3	1571.3	6
1185.0	1	1432.5	5	1573.7	1
1188.1	4	1435.9	6	1577.1	6
1189.8	4	1437.5	3	1579.0	1
1205.1	5	1440.4	7	1581.0	6
1206.7	5	1443.2	5	1583.8	2
1215.6	7	1454.3	4	1585.5	2
1228.3	5	1455.9	1	1587.4	1
1229.9	7	1457.6	3	1588.8	6
1232.0	3	1459.7	3	1591.2	5
1246.2	1	1462.1	4	1593.2	3
1247.6	1	1463.5	4	1595.8	7
1253.8	2	1466.6	4	1599.1	1
1257.2	2	1468.1	4	1601.6	10
1262.0	3	1470.5	1	1604.1	4
1276.7	2	1472.2	1	1604.9	4
1279.3	3	1479.1	2	1607.8	10
1283.2	3	1481.2	2	1610.0	4
1284.6	2	1483.2	2	1611.5	1
1331.6	1	1486.0	8	1613.0	9
1334.1	4	1488.7	7	1614.7	1
1336.0	4	1491.3	3	1616.4	2
1338.8	2	1494.9	10	1620.6	4
1342.5	6	1499.2	2	1623.0	5
1345.2	5	1504.2	2	1625.5	1
1347.2	5	1510.8	4	1628.0	4
1352.5	2	1513.0	4	1633.5	6
1353.6	3	1514.5	4	1636.0	3
1355.5	2	1517.0	5	1640.0	3
1357.5	5	1518.3	5	1641.2	2
1363.5	8	1519.1	1	1642.4	1
1365.6	3	1522.6	6	1644.1	3
1367.8	3	1530.2	4	1702.5	1
1371.1	5	1532.4	4	1810.8	1
1377.1	3	1534.3	2	1877.7	1
1380.4	3	1536.9	4		
1385.7	1	1538.9	1		

λ 1700. No. 1 was obtained after the apparatus had been filled but once with gas and then pumped to a pressure of 2 mm. No. 5 shows the result after the spectroscope had been flushed five times with hydrogen.

Reference has already been made to the paper in which the method of using the comparison spectrum is explained. The above measurements rest on the aluminium lines λλ 1854, 1862.2, 1935.2 . . . . as determined by Runge, and upon lines in the comparison cadmium spectrum. The wave-lengths of these lines are those given by Exner and Haschek. The correction to vacuum was obtained from the work of Kayser and Runge.

The author makes no claim that all of these lines belong to the spectrum of hydrogen. He can only state that an end-on vacuum tube, connected directly to a large brass cylinder filled with pure, dry hydrogen, produces such a spectrum. Under the circumstances, any speculation as to the possible series relations existing between these short wave-lengths would be premature.

The author is at present engaged in an attempt to determine the sources of the lines already observed, by a study of the emission and absorption spectra of other gases in this region.

The present paper is entirely of a preliminary character. It is the author's purpose to publish a more complete description of apparatus and results at some future time.

The chief result of this investigation is the measurement of the short wave-lengths, whose existence was first discovered by Schumann. It is, however, of interest to note that the considerable reflective power of speculum metal for these short waves has incidentally been demonstrated.

JEFFERSON PHYSICAL LABORATORY,
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March 28, 1904.

INVESTIGATIONS ON THE SPECTRUM AND ORBIT OF δ *ORIONIS*.[1]

By J. HARTMANN.

ONE of the first results obtained by M. Deslandres with the new spectrograph attached to the 62 cm refractor of the observatory at Meudon was the discovery of the "oscillation" of δ *Orionis*. I use the term "oscillation" in place of the ponderous expression "variability of velocity in the line of sight;" but the idea of oscillation is still somewhat broader, as it includes every sort of periodic variation in the spectrum, without saying anything as to its explanation.

After the publication[2] of the discovery mentioned, which was communicated to the Paris Academy on February 12, 1900, Director Vogel instructed the observers in the field of stellar spectroscopy at Potsdam to undertake to confirm the interesting phenomenon, and the observations made with the four different spectrographs then in use here proved beyond a doubt that δ *Orionis* belongs to the number of oscillating stars. A confirmation of the discovery was also given by three observations by Wright with the Mills spectrograph of the Lick Observatory.

Deslandres derived from his eleven observations a period of 1.92 days, and concluded that the orbit was very eccentric. The observations which I made at that time with the large Spectrograph III (with three prisms) attached to the 80 cm refractor could not, however, be brought into accord with that length of period; and since the measures showed that the star could be more advantageously observed with low dispersion, on account of the extreme diffuseness of its lines, I included it in the program of Spectrograph I (with only one prism). With this instrument I made in the winter months of 1901–2 and 1902–3 an extensive series of observations, which will now be discussed.

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[1] Translated from advance proofs, sent by the author, with additions, of a paper to appear in the *Sitzungsberichte der Kgl. Akademie der Wissenschaften zu Berlin.*

[2] H. DESLANDRES, "Variations rapides de la vitesse radiale de l'étoile δ *Orion*," *Comptes Rendus*, 130, 379, 1900.

It may be remarked here that my observations have not confirmed the period deduced by Deslandres, the true period exceeding three times the value given by him. The eccentricity is also only slight. It is true, as I have convinced myself, that Deslandres' observations happen to be pretty well represented by a period of 1.92 days, with the exception of his first and last measures, which were

1899, December 8.4, $V = +95$ km; 1900, January 25.3, $V = -50$ km.

If we add twenty-five times the period to the epoch of the first observation, $25 \times 1^d.92 = 48^d.0$, we get 1900, January 25.4, $V = +95$ km, which contradicts the last observation. But the period I have derived well represents all of the observations of Deslandres.

Table I contains the list of my observations, the Roman numerals in the first column being used to designate the spectrograph used. Plates IV 431 and IV 435 were made with Spectrograph IV attached to the 33 cm refractor by Dr. Ludendorff, who also assisted me with the plates taken with Spectrograph I attached to the 80 cm refractor. In the column headed "Julian Day," the first three figures 241 are always omitted, as also later in the text, and the times are always expressed in Greenwich mean time. V is the observed velocity in the line of sight relative to the Sun, and ϵ is the mean error of this number, computed from the internal agreement of the results derived from the different lines. L is the number of lines used in computing the velocity. The last two columns will be explained later.

δ Orionis belongs to the type of *Orion* stars (I*b*), whose spectrum shows, besides the hydrogen lines, chiefly the lines of helium, all of which in this case are exceedingly diffuse and dim, so that their measurement is very difficult and uncertain. On account of the slight intensity of the lines, all defects of the film are very disturbing, and, in consequence of irregular distribution of the silver grains, the lines often appear crooked and unsymmetrical, sometimes indeed double. I have convinced myself by a special investigation that the indications of duplicity and unsymmetrical broadening cannot be caused by lines belonging

TABLE I.

Plate Number	Greenwich M. T.	Julian Day	V	ϵ	L	C	$V-C$
			km	km		km	km
III 41	1900, Feb. 25 6^h48^m	$5076^d.28$	+ 84.0	± 6.0	1	+ 83.6	+ 0.4
III 43	Mar. 1 6 25	5080.27	− 45.4	17.0	2	− 66.4	+21.0
III 49	7 6 8	5086.26	− 49.4	5.0	2	− 58.5	+ 9.1
IV 431	1901, Jan. 5 8 7	5390.34	− 24.5	....	1	− 44.7	+20.2
IV 435	9 8 2	5394.33	− 30.9	....	1	− 28.6	− 2.3
I 153	Nov. 23 10 6	5712.42	+ 63.5	2.9	6	+ 63.3	+ 0.2
I 189	1902, Jan. 13 7 19	5763.30	− 3.3	5.7	8	− 17.4	+14.1
I 191	13 9 35	5763.40	+ 6.1	6.9	9	− 7.8	+13.9
I 196	14 8 32	5764.36	+ 92.2	8.4	10	+103.2	−11.0
I 200	14 10 35	5764.44	+110.5	4.8	8	+110.0	+ 0.5
I 204	16 8 35	5766.36	+ 27.0	3.1	6	+ 23.5	+ 3.5
I 215	Feb. 4 10 11	5785.42	− 65.0	9.1	6	− 65.1	+ 0.1
I 221	10 8 50	5791.37	− 45.1	6.6	6	− 58.0	+12.9
I 224	11 6 9	5792.26	+ 17.8	6.1	6	+ 13.6	+ 4.2
I 226	12 5 46	5793.24	+124.9	9.5	2	+120.5	+ 4.4
I 227	13 5 22	5794.22	+107.1	6.3	6	+104.5	+ 2.6
I 231	14 5 26	5795.23	+ 3.9	6.5	6	+ 3.0	+ 0.9
I 232	15 4 42	5796.20	− 63.0	3.0	6	− 61.1	− 1.9
I 234	16 5 1	5797.21	− 52.3	3.0	7	− 52.9	+ 0.6
I 245	Mar. 5 6 20	5814.26	− 59.6	6.1	8	− 59.8	+ 0.2
I 247	6 5 26	5815.23	+ 27.3	3.3	7	+ 18.0	+ 8.6
I 253	11 7 20	5820.31	− 43.5	3.3	7	− 42.8	− 0.7
I 254	12 5 38	5821.23	+ 45.4	6.2	6	+ 50.6	− 5.2
I 256	13 5 35	5822.23	+128.4	7.0	7	+133.4	− 5.0
I 262	14 5 43	5823.24	+ 68.7	5.5	8	+ 69.8	− 1.1
I 266	April 2 6 13	5842.26	− 79.5	6.6	7	− 66.2	−13.3
I 268	2 7 22	5842.31	− 60.0	5.4	7	− 67.1	+ 7.1
I 284	9 7 6	5849.30	− 30.0	4.7	3	− 15.5	−14.5
I 288	10 6 46	5850.28	+ 81.2	3.8	7	+ 96.4	−15.2
I 475	Dec. 11 9 14	6095.38	− 49.3	4.1	7	− 48.4	− 0.9
I 481	12 8 53	6096.37	+ 47.2	0.8	6	+ 48.0	− 0.8
I 485	13 8 49	6097.37	+128.7	8.9	6	+133.2	− 4.5
I 491	14 11 1	6098.46	+ 56.1	4.9	6	+ 63.5	− 7.4
I 494	1903, Jan. 9 8 7	6124.34	− 32.7	7.7	8	− 26.5	− 6.2
I 495	12 9 23	6127.39	+ 38.2	7.1	8	+ 35.8	+ 2.4
I 501	13 8 12	6128.34	− 46.4	6.2	7	− 45.2	− 1.2
I 505	14 7 40	6129.32	− 69.3	3.5	5	− 66.4	− 2.9
I 509	17 8 32	6132.36	+127.1	7.5	9	+111.0	+16.1
I 523	Feb. 7 8 51	6153.37	0.0	2.3	7	+ 9.2	− 9.2
I 527	Mar. 7 5 28	6181.23	− 54.9	6.0	9	− 55.8	+ 0.9
I 535	12 5 51	6186.24	− 61.2	7.3	9	− 66.7	+ 5.5
I 541	15 6 9	6189.26	+135.4	5.2	6	+132.7	+ 2.7

to a second component of the stellar system; but I do not hold it to be impossible that the form of the lines is subject to small real changes, perhaps in consequence of violent motions in the gaseous envelope of the star.

Although we must, accordingly, regard δ *Orionis* as a binary system having one of its components "dark," in the customary phrase, I would nevertheless point out that by "dark" we here must understand only a relatively small difference of brightness. A difference of only about one magnitude would be sufficient to bring the spectrum of the fainter component to almost complete disappearance, and a difference of two magnitudes would make it impossible for even a trace of the fainter spectrum to be visible on the plate. The slight difference of magnitude necessary for the extinction of the fainter spectrum explains the fact that among the numerous spectroscopic binaries so far discovered there are very few which show the lines of the second component in the spectrum.

The great diffuseness of the lines of this spectrum gives large play to personality effects of the observer, and in order to reach trustworthy results it is therefore necessary that everything subjective should be, as far as possible, eliminated from the observations. To this end I have observed the following rules in these measurements, which were all made by myself: In the first place every plate was measured wholly independently in the two positions of the plate, violet toward the right and violet toward the left. While this procedure is to be highly recommended even for spectra with sharp lines, as I have elsewhere shown,[1] it is wholly essential for diffuse lines, since here the psycho-physical errors in the estimates of the centers of the lines reach extremely high values. Secondly, every prepossession of the observer was most strictly avoided during the measurements, the reduction of the observations and the drawing of the velocity curve not being undertaken until all the measures had been entirely concluded. Finally, in order to obtain as accurate velocities as possible, and fully to dispose of the data of the plate employed in this discussion, I adopted the rule of measuring *all* of the lines that could be recognized on each plate. Thus I have been able to measure twenty different lines in all, while the measures of all earlier observers using high dispersion were limited to the $H\gamma$ line. For the determination of the velocity itself, however, only those lines could be used which permitted a fairly safe measurement on the majority of the plates and whose wave-lengths were known with sufficient accuracy. The following eleven lines were of this kind:

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[1] *Astronomische Nachrichten*, 155, 97, 1901.

TABLE II.

Name	Element	λ
Hζ	*H*	3889.20
Hε	*H*	3970.23
	He	4026.34
	Si	4089.00
Hδ	*H*	4101.89
Hγ	*H*	4340.64
	He	4388.10
	He	4471.65
	Mg	4481.38
Hβ	*H*	4861.50
	He	4922.10

The wave-lengths of the nine remaining lines, which are collected in Table III, I have calculated from measurements in the star spectrum itself. On account of the exceeding difficulty of their measurement, they are indeed rather unreliable, as is shown by the mean error given in the third column, but they are nevertheless sufficient to render possible an accurate identification in connection later with other stars of the same type.

TABLE III.

λ	No. of Plates	Mean Error	Remarks
3933.68	7	(± 0.34)	*Ca;* always exceedingly weak and narrow.
4069.49	3	± 0.16	
4097.40	5	0.14	*Si*
4116.28	11	0.07	*Si*
4144.94	2	0.28	
4200.42	2	0.20	*Hδ'* according to Pickering's nomenclature.
4541.78	2	0.41	*Hγ'* according to Pickering's nomenclature.
4649.68	10	0.14	Probably a group; 4 tenth-meters wide.
4686.20	10	0.12	

Among the lines in Table III the calcium line at λ 3934 exhibits a very peculiar behavior. It is distinguished from all the other lines of this spectrum, first by the fact that it always appears extraordinarily weak, but almost perfectly sharp; and it therefore attracted my attention that in computing the wave-lengths collected in Table III for this particular line, the agreement between the results from the different plates was decidedly less than for the other, much less sharp lines. Closer study on this point now led me to the quite surprising result *that the calcium line at λ 3934 does not share in the periodic displacements of the lines caused by the orbital motion of the star.*

As appears from Table III, I had in the first measurement of the negatives measured this line on seven plates, on which it was particularly well recognizable. In order fully to assure the peculiar result found, I then subjected the whole set of plates to another examination, when in all twelve were found on which the line could be measured with accuracy. The results of this second measurement, which was of course again carried out with the strictest avoidance of all prepossession, are contained in the column headed II in Table IV, the original measurements being given in column I. In this table I have arranged the plates in order of the values of V, the true velocity of the star relative to the Sun, computed from the orbit. The velocities deduced from the calcium line alone are designated by C' (relative to the Earth), and C (relative to the Sun).

TABLE IV.

Plate Number	V	C' from λ 3934			Reduction to Sun	C	Diff.
		I	II	Mean			
	km	km	km	km	km	km	km
I 247	+ 18.0	+44	+39	+42	−27	+15	− 1
I 254	+ 50.6	....	+44	+44	−27	+17	+ 1
I 153	+ 63.3	+11	+11	+11	+ 9	+20	+ 4
I 485	+133.2	+24	+19	+22	0	+22	+ 6
I 491	+ 63.5	+ 3	+ 7	+ 5	− 1	+ 4	−12
I 495	+ 35.8	....	+38	+38	−14	+24	+ 8
I 204	+ 23.5	+35	+25	+30	−16	+14	− 2
I 231	+ 3.0	....	+40	+40	−25	+15	− 1
I 232	− 61.1	+25	+32	+28	−25	+ 3	−13
I 266	− 66.2	+46	+49	+48	−26	+22	+ 6
I 215	− 65.1	....	+43	+43	−23	+20	+ 4
I 221	− 58.0	....	+42	+42	−24	+18	+ 2
						Mean +16 km	

As appears from the differences from the mean, given in the last column, the values of C are wholly independent of V, and hence of the orbital position of the star; they are also in as good agreement as could be expected in view of the difficulty of the measurements.

The fact being thus fully established that a single line of the spectrum does not participate in the oscillatory motion of the other lines, the question arises as to how it can be explained. The character of the absorption corresponding to the line makes it highly improbable that it should have originated in the Earth's atmosphere. In that case, moreover, the line in question would have to appear in every stellar spectrum, and the velocities C' computed from its position would come into worse agreement on applying the correction for reduction to the Sun. But the case is quite the opposite—the value of C does not become constant until after applying the reduction to the Sun, and thus the cosmical origin of the line is proven.

The most natural assumption, that the observed line belongs to the second component of the binary system, encounters two difficulties. Since the values of C in Table IV indicate no dependence upon V, we should have to assume for the fainter component a mass *at least* ten times as great as that of the brighter star. While this is itself very improbable, it is still more surprising that not a single other line should be revealed of the spectrum of the second body. The occurrence of such an isolated line would be explained by none of the spectral types hitherto known, and it points rather with a pretty fair degree of certainty to the presence of an absorbing layer of gas not in immediate connection with the star.

We are thus led to the assumption that at some point in space in the line of sight between the Sun and δ *Orionis* there is a cloud which produces that absorption, and which recedes with a velocity of 16km, in case we admit the further assumption, very probable from the nature of the observed line, that the cloud consists of calcium vapor. This reasoning finds a distinct support in a quite similar phenomenon exhibited by the spectrum of *Nova Persei* in 1901. While the lines of hydrogen and other elements in that spectrum led us, by their enormous broadening and displacement and the continuous changing of their form, to conclude that stormy processes were going on within the gaseous envelope of the star, the two calcium lines at λ 3934 and λ 3969, as well as the D lines, were observed as perfectly sharp absorption lines, which yielded the constant velocity of + 7 km during the whole duration of the phenomenon. I then expressed the opinion that these sharp lines probably did not have their origin in the *Nova* itself, but in a nebulous mass lying in the line of sight—a view which only gained in probability on the later discovery of the nebula in the neighborhood of the *Nova*. In the case of δ *Orionis* also it is not unlikely that the cloud stands in some relation to the extensive nebulous masses shown by Barnard[1] to be present in the neighborhood. The second calcium line at λ 3969 is concealed in the spectrum of δ *Orionis* by the broad hydrogen line $H\epsilon$, and therefore cannot be observed.

I would also call attention at this point to a further peculiar phenomenon. If we compute the component of the solar motion $V_\odot$ according to Campbell's[2] provisional elements of the apical motion, we obtain:

for δ *Orionis* - $V_\odot = + 18.1$ km
for *Nova Persei* $V_\odot = + 8.7$ km

These figures agree within the errors of observation with the observed velocity of the calcium clouds, which therefore in these two cases are almost completely at rest relatively to the 280 stars employed by Campbell.

The point in the line of sight at which the nebulous mass lies cannot be ascertained. In order to determine its lateral extension the spectra of neighboring stars, particularly those with variable or distinctly different velocity, should be examined for the occurrence of the calcium line. It is present in the spectrum of ε and ζ *Orionis*, but inasmuch as the velocities of these stars differ only slightly from the motion of the cloud given above, we cannot distinguish whether it belongs to the spectrum of the star or of the cloud.

In a similar manner I have also tested the behavior of the other lines of Table III, but I am unable to detect anything similar in the case of any one of them.

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[1] "Diffused Nebulosities in the Heavens," ASTROPHYSICAL JOURNAL, **17**, 77, 1903.

[2] "A Preliminary Determination of the Motion of the Solar System," *ibid.*, **13**, 80, 1901.

After these remarks on the spectrum of δ *Orionis*, I now proceed to the determination of the orbit.

The observations on seven successive days in February 1902 first proved beyond a doubt that the period was not 1.92 days, but from five to six days. Successive plates taken on the same evenings (1902, January 13, January 14, and April 2) showed that the period could not be still shorter, as has been suspected by Deslandres. The inclusion of successively more widely separated observations then gave in the customary manner the provisional value of the period $5^{d}.7333$. This value is accurate to $0^{d}.001$, and is therefore sufficient for reducing all observations of each winter to one revolution, and thus to make it possible to draw the velocity curve.

At first I drew this curve separately for the different years, since it looked as if the orbit might be markedly variable with the time. Four observations by Vogel and Scheiner in the years 1888 to 1891 did not permit of recognition of any variation in the star's velocity. These are given on p. 100 of Part I of Vol. VII of the Publications of the Astrophysical Observatory at Potsdam, and are as follows:

1888,	December 10.37	— 2.7 km
1889,	January 5.34	— 0.1
1891,	February 26.26	+ 2.4
	February 27.26	+ 3.7

Then followed in 1899 and 1900 the observations of Deslandres, of Wright, and of the writer, which yielded velocities from — 69 to + 95 km, and finally my measures in 1902 and 1903 indicated a range from — 79.5 to + 135.4 km. The amplitude of the variation accordingly appeared to increase greatly, which could have been readily explained by the assumption of a change in the inclination of the plane of the orbit to the line of sight.

On this point the Potsdam plates from 1888 to 1891 were now decisive. On computing backward with the given period and the present range of velocity, it appeared that the first two early observations happened to have been made at times when the velocity of the star was actually very small, so that the variability might easily escape the observers. *Per contra*, at the third observation the velocity must have been about —50 km, and at the fourth, about + 50 km, whence the variation should have been detected with certainty on those plates, in case the amplitude of variation had not actually changed in the meantime. Professor Vogel was therefore kind enough to remeasure the four plates, and found for the first and second plates a confirmation of the former results, but he experienced a decided change in his impression as to the settings (*Auffassung*) for the third and fourth plates. On those early plates the artificial hydrogen line fell across the star spectrum, so that the observation was rendered exceedingly difficult, particularly for stars of the first type, in which only the diffuse $H\gamma$ line was measured. Doubtless as the result of the good agreement of the first two plates, the observers measured the third and fourth plates with an incorrect *Auffassung* of the line. The remeasurement led to the following velocities:

— 8.8 km
+ 3.7
— 55.0
+ 13.3

These agree so well with the present motion that we may abandon the assumption of a change in the orbit. The observations of 1899 and 1900 further do not of themselves force us to this assumption. The dates of the observations fall so that the maximum positive velocity never happened to be observed, whence the amplitude would appear to be smaller. As I shall show farther on, these observations can also be accurately represented by the present orbit. Finally, the two velocity curves drawn from my observations in the winters of 1901–2 and 1902–3 were perfectly similar and could be accurately superposed. For these reasons I gave up my original plan of computing an independent orbit for each season's observations, and my orbit is based upon my whole series of observations made with Spectrograph I in the winters of 1901–2 and 1902–3. I decided not to employ the older measures for the orbit, first, because all these determinations made with higher dispersion are decidedly less accurate, and second, because a slight alteration in the assumed period of revolution would have too strongly affected these remote observations. Therefore I have employed the early Potsdam series only for deriving the definitive period.

I adopted the following method for transferring with entire certainty the observations of the winter of 1902–3 to the preceding year. After velocity-curves had been drawn separately for the two years, as already stated, the times were read off on the two curves, both on the ascending and descending branches, at which the velocities were $-50, -40, \cdots +100, +110$ km. In this way were obtained thirty-four determinations of the difference in time by which the second curve (from observations of 1902–3) must be displaced in order to superpose it upon those of 1901–2. The mean of the thirty-four differences was $332^{d}.53$; since this number is equal to fifty-eight revolutions, the result follows: $P = 5^{d}.7333$, which happens to agree precisely with the value given above.

After all of the thirty-seven plates made with Spectrograph I had been in this way transferred to the single revolution of 1902, February 10–16, the elements of the orbit were determined by the method of Lehmann-Filhés[1] with the following result:

ELEMENTS.

Velocity of the center of gravity - $V_0 = +23.1$ km
Epoch of periastron - - $T = 5793.35 = 1902$, Feb. 12.35
Epoch for $V = 0$ - - - - $t_0 = 5792.13 = 1902$, Feb. 11.13
Longitude of the perihelion (from ☊) $\omega = 33^\circ\ 18'.9$
Longitude of the farthest point of the orbit - - - - $u_1 = 95^\circ\ 32'.9$
Longitude of the nearest point of the orbit - - - - $u_2 = 264^\circ\ 27'.1$
Eccentricity - - - - $e = 0.10334$
Projection of semi-major axis on the line of sight - - - $a \sin i = 7906600$ km
Ratio of masses - - $\frac{m_2^3 \sin^3 i}{(m_1 + m_2)^2} = 0.601\,\odot$

Since we do not know the inclination of the orbit to the tangential plane passing through the center of gravity of the orbit perpendicular to the line of sight, the value of the semi-axis a cannot be computed, but we can give the distances which the visible star reaches behind and in front of this plane, to which the longitudes designated above with u_1 and u_2 correspond. It results that the star moves as far as 8069400 km behind this plane and out to 7498500 km in front of the plane. If we make the following assumptions as to the inclination, we get these results:

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[1] *Astronomische Nachrichten*, 136, 17, 1894.

$i = 45^\circ$	$a = 11182000$ km
60°	9129800
75°	8185600
90°	7906600

We see from this that the orbit has something like one-sixth the diameter of the orbit of *Mercury*, in case we do not assume i to be very small. If the masses of the two components of the binary system are nearly equal—a point which I shall presently discuss more fully—the separation of the stars would accordingly be about one-third of the distance of *Mercury* from the Sun.

Since nothing is known as to the motion of the second component, we can compute for the mass of the system only the relation given above,

$$\frac{m_2^3 \sin^3 i}{(m_1 + m_2)^2} = 0.601 \odot ,$$

in which m_1 is the mass of the visible, and m_2 that of the invisible, star. Here also we can reach at least approximate estimates of the true relations by reasonable assumptions.

All spectroscopic binaries for which it has been possible to observe the second component consist of two stars of nearly equal mass, and it can be shown also in the case before us that a dark star cannot be essentially smaller than the visible one. If we first calculate the very improbable case $m_2 = 5m_1$, that is, where the dark star is five times as massive as the bright one, we get

$$\begin{aligned} m_2 \sin^3 i &= 0.865 \odot \\ m_1 \sin^3 i &= 0.173 \odot \\ \hline (m_1 + m_2) \sin^3 i &= 1.038 \odot . \end{aligned}$$

Therefore in this case the total mass of the system would certainly be larger than that of the Sun. Similarly if we make the calculations for the assumptions $m_1 = m_2$, $m_1 = 5m_2$, and $m_1 = 10m_2$, we shall obtain the values of the masses given in Table V.

TABLE V.

	$m_1 \sin^3 i$	$m_2 \sin^3 i$	$(m_1 + m_2) \sin^3 i$
$m_1 = 0.2m_2$	0.173 $\odot$	0.865 $\odot$	1.038 $\odot$
$m_1 = m_2$	2.404	2.404	4.808
$m_1 = 5m_2$	108.2	21.6	129.8
$m_1 = 10m_2$	727.2	72.7	799.9

As the table shows, if we assume m_1 to be notably larger than m_2, we reach enormous masses, quite aside from the factor $\sin^3 i$, and therefore it may be regarded as most probable that the two masses are nearly equal for the case of *δ Orionis*. If we now repeat the computations for the previously assumed values of i, on the assumption that $m_1 = m_2$, we get

$i = 45°$	$m_1 + m_2 = 13.6 \odot$
60	7.4
75	5.3
90	4.8

We see from these considerations that the total mass of the system is certainly greater than the solar mass, and probably of the order of from five to ten times the solar mass.

In order to facilitate the comparison with the calculated orbit of the observations at present before us, as well as possible later ones, I have computed the ephemeris given in Table VI from the above elements. The argument τ is reckoned from that point of time at which V passes through zero when increasing, and which is obtained from $t_0 + nP$, where n is a whole number.

I have now employed this ephemeris in the following manner, in order to employ the early Potsdam observations in deriving the definitive period: If the early observation gave the velocity V at the time t, the value of τ corresponding to T is sought in Table VI, and the time $t_0 + \tau$ then corresponds to the same point of the orbit as t, so that $t_0 + \tau - t$ is always a whole number of periods. The approximate period is sufficient for previously determining whether τ falls on the ascending or descending part of the curve.

TABLE VI.

T	0d	1d	2d	3d	4d	5d
d	km	km	km	km	km	km
0.00	+ 0.0	+112.3	+111.7	+12.6	−58.7	−56.8
01	1.0	113.1	111.0	11.6	59.0	56.3
02	2.0	113.9	110.2	10.6	59.4	55.8
03	3.0	114.6	109.4	9.7	59.8	55.4
04	4.0	115.4	108.6	8.7	60.2	54.9
05	+ 5.0	+116.1	+107.8	+ 7.8	−60.5	−54.4
06	6.0	116.9	107.0	6.8	60.8	53.9
07	7.0	117.6	106.2	5.9	61.1	53.4
08	8.1	118.3	105.4	4.9	61.4	52.9
09	9.2	119.0	104.5	4.0	61.7	52.4
0.10	+10.3	+119.8	+103.7	+ 3.0	−62.0	−51.8
11	11.4	120.5	102.8	2.1	62.3	51.3
12	12.5	121.2	102.0	1.1	62.6	50.7
13	13.6	121.8	101.1	+ 0.2	62.9	50.2
14	14.7	122.4	100.2	− 0.8	63.1	49.6
15	+15.8	+123.1	+ 99.3	− 1.7	−63.4	−49.0
16	16.9	123.7	98.4	2.7	63.6	48.4
17	18.0	124.3	97.5	3.6	63.9	47.8
18	19.2	124.8	96.5	4.5	64.2	47.2
19	20.3	125.4	95.6	5.4	64.4	46.6
0.20	+21.5	+125.9	+ 94.6	− 6.4	−64.7	−46.0
21	22.6	126.4	93.7	7.3	64.9	45.4
22	23.8	127.0	92.7	8.2	65.1	44.7
23	25.0	127.5	91.7	9.2	65.4	44.1
24	26.2	128.0	90.7	10.1	65.6	43.4
25	+27.3	+128.4	+ 89.8	−11.0	−65.8	−42.8
26	28.5	128.9	88.8	11.9	66.0	42.1
27	29.7	129.3	87.8	12.8	66.2	41.4
28	30.9	129.7	86.8	13.7	66.4	40.7
29	32.1	130.1	85.8	14.6	66.6	40.0
0.30	+33.4	+130.4	+ 84.9	−15.4	−66.7	−39.3
31	34.6	130.8	83.9	16.2	66.9	38.6
32	35.8	131.1	82.9	17.0	67.1	37.8
33	37.0	131.4	81.9	17.8	67.3	37.1
34	38.2	131.6	80.9	18.6	67.4	36.3
35	+39.5	+131.9	+ 80.0	−19.4	−67.5	−35.6
36	40.7	132.1	79.0	20.2	67.6	34.8
37	41.9	132.4	78.0	21.0	67.7	34.0
38	43.1	132.6	77.0	21.8	67.7	33.2
39	44.3	132.7	76.0	22.6	67.8	32.4
0.40	+45.6	+132.9	+ 74.9	−23.4	−67.9	−31.6
41	46.8	133.0	73.9	24.2	67.9	30.8
42	48.0	133.2	72.9	24.9	68.0	29.9
43	49.3	133.3	71.9	25.7	68.0	29.1
44	50.6	133.4	70.8	26.4	68.0	28.2
45	+51.8	+133.5	+ 69.8	−27.2	−68.0	−27.3
46	53.1	133.6	68.7	27.9	68.0	26.5
47	54.4	133.7	67.7	28.6	68.0	25.6
48	55.7	133.7	66.7	29.4	68.0	24.7
49	57.0	133.7	65.6	30.2	68.0	23.8

TABLE VI.—*Continued.*

τ	0^d	1^d	2^d	3^d	4^d	5^d
	km	km	km	km	km	km
$0^d.50$	+ 58.2	+133.7	+64.6	−30.9	−68.0	−22.9
51	59.5	133.7	63.5	31.6	68.0	22.0
52	60.8	133.7	62.5	32.3	68.0	21.1
53	62.0	133.6	61.5	33.0	68.0	20.2
54	63.3	133.5	60.4	33.7	67.9	19.3
55	+ 64.5	+133.4	+59.4	−34.3	−67.9	−18.3
56	65.8	133.3	58.3	35.0	67.8	17.4
57	67.0	133.1	57.3	35.7	67.8	16.4
58	68.2	132.9	56.2	36.4	67.8	15.5
59	69.4	132.7	55.2	37.0	67.7	14.5
0.60	+ 70.5	+132.5	+54.1	−37.7	−67.7	−13.5
61	71.7	132.3	53.1	38.3	67.6	12.5
62	72.9	132.0	52.0	39.0	67.5	11.5
63	74.1	131.7	50.9	39.7	67.4	10.5
64	75.3	131.4	49.8	40.3	67.3	9.5
65	+ 76.4	+131.1	+48.8	−41.0	−67.2	− 8.5
66	77.6	130.8	47.7	41.6	67.0	7.5
67	78.8	130.4	46.6	42.2	66.9	6.5
68	80.0	130.0	45.5	42.8	66.8	5.5
69	81.2	129.7	44.4	43.4	66.6	4.5
0.70	+ 82.4	+129.3	+43.4	−44.0	−66.4	− 3.5
71	83.6	129.0	42.3	44.6	66.2	2.5
72	84.8	128.6	41.2	45.2	66.0	1.4
73	86.0	128.1	40.1	45.8	65.8	− 0.4
74	87.2	127.7	39.0	46.4	65.6	+ 0.7
75	+ 88.3	+127.2	+38.0	−46.9	−65.4	+ 1.7
76	89.5	126.8	36.9	47.5	65.1	2.8
77	90.7	126.3	35.8	48.1	64.9	3.9
78	91.8	125.8	34.8	48.7	64.6	4.9
79	93.0	125.3	33.7	49.2	64.4	6.0
0.80	+ 94.1	+124.8	+32.7	−49.7	−64.1	+ 7.1
81	95.3	124.3	31.6	50.2	63.9	8.2
82	96.4	123.8	30.6	50.7	63.6	9.3
83	97.4	123.3	29.6	51.2	63.3	10.4
84	98.4	122.7	28.6	51.7	63.0	11.5
85	+ 99.4	+122.2	+27.5	−52.2	−62.7	+12.6
86	100.4	121.6	26.5	52.6	62.3	13.7
87	101.4	121.0	25.5	53.1	62.0	14.8
88	102.3	120.4	24.5	53.6	61.7	15.9
89	103.2	119.7	23.5	54.0	61.4	17.1
0.90	+104.1	+119.1	+22.5	−54.5	−61.0	+18.3
91	105.1	118.4	21.5	55.0	60.6	19.5
92	106.0	117.7	20.5	55.4	60.2	20.7
93	106.8	117.0	19.5	55.9	59.8	21.8
94	107.6	116.2	18.5	56.3	59.4	23.0
95	+108.4	+115.5	+17.5	−56.7	−58.9	+24.2
96	109.2	114.7	16.5	57.1	58.5	25.4
97	110.0	114.0	15.5	57.5	58.0	26.6
98	110.8	113.2	14.5	57.9	57.6	27.8
99	111.6	112.5	13.5	58.3	57.2	29.0

Table VII contains the computation of P from the early Potsdam observations by this procedure, which makes possible the use of each isolated early observation, and which assigns to each observation its appropriate weight in taking the mean.

TABLE VII.

Observer	t	V	τ	$t_0+\tau-t$	n	P
		km				
Vogel-Scheiner	$982^d.37$	-8.8	$5^d.65$	$4815^d.41$	840	$5^d.7326$
	1008.34	$+3.7$	3.09	4786.88	835	5.7328
	1790.26	-55.0	5.04	4006.91	699	5.7323
	1791.26	$+13.0$	0.13	4001.00	698	5.7321

On summing up the numbers $t_0+\tau-t$ and n, we obtain

$$3072\,P = 17610^d.20$$
$$P = \quad 5.7325$$

Deslandres' observations could not be used for a determination of the period, since the times of the observations were not exactly given by him; and this is also the case with the plates obtained with high dispersion in the years 1900 and 1901. The computation for the series in the winter of 1902–3 is given in Table VIII. The observations have been here omitted which would yield an uncertain value of τ on account of their position in the neighborhood of the points of inflection of the velocity-curve.

TABLE VIII.

Observer	t	V	τ	$t_0+\tau-t$	n	P
		km				
Hartmann	$6095^d.38$	-49.3	$5^d.14$	$298^d.11$	52	$5^d.7329$
	6096.37	$+47.2$	0.41	303.83	53	5.7326
	6098.46	$+56.1$	2.58	303.75	53	5.7311
	6124.34	-32.7	5.39	326.82	57	5.7337
	6127.39	$+38.2$	2.75	332.51	58	5.7329
	6128.34	-46.4	3.74	332.47	58	5.7322
	6153.37	0.0	0.00	361.24	63	5.7340
	6181.23	-54.9	5.04	384.06	67	5.7322

Hence

$$461\,P = 2642^d.79$$
$$P = \quad 5.7327$$

On combining this with the previous result we finally get

$$3533\,P = 20252^{d}.99$$

whence follows the definitive value of the period of revolution

$$P = 5^{d}.7325 \pm 0^{d}.0002 \text{ or } 5^{d}\,17^{h}\,34^{m}\,48^{s} \pm 17^{s}\,.$$

With the aid of the ephemeris, and using this value of the period, I now made a comparison of all observations with the computed orbit. For my own observations this comparison is contained in the last two columns of Table I. Some of the residuals *V–C* are of very considerable size, in accordance with my remarks above as to the uncertainty of the measures. The mean error of one plate with Spectrograph I is found from the sum of the squares of the residuals to be ± 8.0 km. The uncertainty of the plates taken with higher dispersion is decidedly larger, as may be seen from the similar comparison for the other observers given in Table IX. I have put in reasonable estimates for the times of observations of Deslandres and Wright, which were not given exactly.

TABLE IX.

Observer	Date	Julian Day	*V*	*C*	*V–C*
			km	km	km
Vogel-Scheiner	1888, Dec. 10	$0982^{d}.37$	− 8.8	− 19.3	+10.5
	1889, Jan. 5	1008.34	+ 3.7	+ 27.5	−23.8
	1891, Feb. 26	1790.26	−55.0	− 49.0	− 6.0
	27	1791.26	+13.3	+ 48.0	−34.7
Deslandres	1899, Dec. 8	4997.42	+95	+102.8	− 7.8
	9	4998.42	−15	+ 2.1	−17.1
	12	5001.42	+70	+ 43.1	+26.9
	15	5004.42	−38	− 21.8	−16.2
	18	5007.42	+81	+ 75.3	+ 5.7
	1900, Jan. 9	5029.38	−37	− 31.6	− 5.4
	10	5030.38	+64	+ 78.8	−14.8
	12	5032.38	+80	+ 46.6	+33.4
	13	5033.38	−49	− 42.2	− 6.8
	18	5038.34	+14	+ 22.5	− 8.5
	25	5045.34	−50	− 63.9	+13.9
Wright	1900, Aug. 12	5244.08	+ 3	− 3.6	+ 6.6
	21	5253.06	+51	+ 80.0	−29.0
	Sept. 17	5280.92	−69	− 66.0	− 3.0

We see at once from the values of the last column that the precision of measurement was of the same order for all of the observers.

After completing the determination of the orbit, I made a further investigation as to the behavior of all the separate lines used for measuring the velocity. For this purpose I arranged in order, according to the orbital position of the star, all the velocities calculated from each separate line, as well as all the remarks which were noted as to the appearance of the lines during the measurement of the plates. It appeared in this way that the residual errors of the individual lines, as well as the unsymmetrical diffuseness, the apparent doubling, and similar phenomena, occurred at all points of the orbit without any evidence of regularity, so that no further conclusions could be drawn at this time on this subject.

It remains for me to discuss in a few words the effect of the velocity of light upon this determination of the orbit. This effect would in general involve three corrections: the first, known under the name of the equation of light, due to the periodic variation of the distance of the Earth from the observed star in the course of a year; the second, quite analogous, due to the distance changing periodically during the period P; and the third, due to the linear increase of the path of the light with the velocity V_0. In the case before us the first two of these equations are entirely negligible. The maximum effect of the equation of light on the *difference* of two times of observations amounts to $11^m\ 18^s = 0\overset{d}{.}0078$, and is therefore of a vanishing order, since all the times of observation were only given to $0\overset{d}{.}01$, corresponding to the accuracy of the measures. The same thing holds good for the light-equation in the orbit of the star, which reaches a maximum of $52^s = 0\overset{d}{.}0006$. But the third correction is, on the contrary, distinctly appreciable. In consequence of the increasing of the distance of the star with the velocity $V_0 = 23.1$ km, the period P appears to us longer by $38\overset{s}{.}02$ than the true period P_1, which accordingly is only $5^d\ 17^h\ 34^m\ 9\overset{s}{.}98 = 5\overset{d}{.}73206$. The above elements of the orbit, particularly $a \sin i$, were computed with this value of P_1.

It may be remarked in conclusion that the light of δ *Orionis* is suspected of variation. John Herschel believed he could detect a variation of the brightness, and the star has been since then often observed, but with contradictory results. Auwers[1] established in 1854, and followed until 1858, a regular variation of the light with a period of $16^{d}.08$, which is nearly equal to three times the period found above. Later observers regarded the variations as only apparent and due to the difficulty of observing this star on account of its low altitude. It is, in any case, to be desired that as sharp as possible a series of photometric measurements should be made for the definitive settlement of the question. In case the star is partially eclipsed by its companion, and hence belongs to the Algol type, the approximate times of minima could be computed from the formula 1902, Feb. 14. 02 $+ nP$.

ASTROPHYSICAL OBSERVATORY, POTSDAM,
March 10, 1904.

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[1] *Astronomische Nachrichten*, **50**, 103, 1859.

MINOR CONTRIBUTIONS AND NOTES.

STARS HAVING PECULIAR SPECTRA.[1]

AN examination of the photographs of the *Henry Draper Memorial* has led to the discovery by Mrs. Fleming of a number of variable stars and objects having peculiar spectra, in addition to those previously published. A list of these has been compiled by Mrs. Fleming, and is given in the table, together with a number of other variables found as described in the remarks following the table. The constellation and catalogue designation are given in the first two columns. The approximate right ascension and declination for 1900, and the catalogue magnitude, are given in the third, fourth, and fifth columns. The class of spectrum, a brief description of the object, and the name of the discoverer are given in the sixth, seventh, and eighth columns. The designations for stars north of declination $-23°$ are taken from the *Bonn Durchmusterung*, for stars between declinations $-23°$ and $-52°$ the *Cordoba Durchmusterung* is used, and for stars south of declination $-52°$ the *Cape Photographic Durchmusterung* is used. Each of these variables has been confirmed independently by a second observer.

Constellation	Designation	R. A. 1900	Dec. 1900	Mag.	Spectrum	Description	Discoverer
Taurus	....	$5^h46^m.9$	+15 57	....	....	Variable	W. P. Fleming
Auriga	+42°.1571	6 27.6	+42 34	9.3	N.	Variable	W. P. Fleming
Canis Minor..	....	7 42.8	+5 44	....	....	Variable	L. D. Wells
Vela	−46.3951	8 11.7	−46 10	7.1	B 3 A	*Hβ* bright	A. J. Cannon
Vela	−48.4658	9 20.4	−48 26	10.0	Md.	Variable	W. P. Fleming
Carina	....	9 35.9	−59 38	....	Br. lines	Gaseous nebula	W. P. Fleming
Carina	57.2781	10 8.3	−57 33	6.7	B 3 A	*Hβ* bright	W. P. Fleming
Carina	....	10 32.8	−70 12	....	Md.	Variable	W. P. Fleming
Vela	−47.6614	11 8.6	−47 40	9.9	Pec.	Dark bands	W. P. Fleming
Ursa Major ..	+58.1346	11 51.3	+58 25	7.5	Md.	Variable	E. S. King
Crux	....	12 50.7	−57 21	....	Pec.	Variable	W. P. Fleming
Centaurus ...	−56.5650	13 7.6	−56 26	9.4	....	Variable	S. E. Breslin
Virgo	−18.3640	13 31.0	−19 5	9.0	....	Variable	W. P. Fleming
Ara	−45.11383	17 11.6	−45 52	10.0	N.	Variable	L. D. Wells
Lyra	+28.3055	18 37.6	+28 43	9.3	Mc.	Variable	W. P. Fleming
Telescopium ..	50.12918	20 12.9	−50 8	10.0	N.	Variable	L. D. Wells
Capricornus .	−16.5558	20 13.3	−16 10	8.0	Mc.	Variable	W. P. Fleming
Cygnus	+40.4393	20 58.9	+40 54	8.4	....	Variable	J. A. Dunne
Indus	−54.9810	21 3.1	−54 7	10.0	Pec.	Dark bands	W. P. Fleming
Cepheus	....	22 12.9	+55 7	....	Br. lines	Type V	W. P. Fleming
Lacerta	....	22 19.9	+50 28	....	Br. lines	Gaseous nebula	W. P. Fleming
Pegasus	....	22 59.2	+14 45	....	....	Variable	E. C. Pickering

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[1] *Harvard College Observatory Circular* No. 76.

REMARKS.

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5 46.9 Found by comparison of photographic charts while identifying Anderson's variable star *Z Tauri*. Measures of one hundred and fifty-seven plates, taken between December 16, 1885, and April 24, 1903, show a variation in magnitude from 11.7 to 14.5.

7 42.8. An examination of twenty-two plates, taken between February 22, 1886, and February 19, 1903, shows a variation of about half a magnitude in the preceding and northern of two faint adjacent and nearly equal stars. This deviation although small, seems to be real, as sometimes one and sometimes the other is the brighter of the two stars. Their distance apart is about 25".

8 11.7. Miss Cannon finds that the line $H\beta$ is bright in the spectrum of this star, and suspects that this line is variable.

9 20.4. Spectrum type III, having also the lines $H\delta$ and $H\gamma$ bright.

9 35.9. A very faint gaseous nebula.

10 32.8. Spectrum Type III, having also the lines $H\delta$ and $H\gamma$ bright.

11 8.6. In the spectrum of this star a strong dark band extends from about λ465 to 471. This band seems to have the same wave-length as the strong bright band in *H.P.* 1311, and similar spectra of Type V.

11 51.3. Found from peculiarity of its spectrum, which is of Type III, having also the lines $H\delta$ and $H\gamma$ bright. An examination of twenty-two plates, taken between November 9, 1897, and March 13, 1904, shows a variation of at least 1.5 magnitudes.

12 50.7. In the spectrum of this star a strong dark band extends from about λ465 to 471, and it closely resembles the spectrum of —47°6614, except that the lines $H\gamma$ and $H\beta$ are bright. No other star has, so far, been found showing these peculiarities in its spectrum.

13 7.6. Found from photographic charts, while measuring magnitudes of — *Centauri*, —56°5632. It was originally the comparison star *n* for this variable.

13 31.0. Found by comparison of photographic charts while looking for asteroid found on Plate A 3078, taken on June 8, 1898.

17 11.6. An examination of nine plates, taken between June 24, 1893, and June 20, 1901, shows a variation of about 1.0 magnitude.

18 37.6. An examination of eighteen photographic charts, taken between July 21, 1892, and May 1, 1903, shows a variation of about 0.8 magnitude.

20 12.9. An examination of ten plates, taken between August 25, 1889, and July 30, 1902, shows a variation of about 0.7 magnitude.

20 58.9. Found in 1901, by Mr. Dunne, from observations with the meridian circle. An examination of nineteen plates, taken between November 6, 1889, and July 12, 1900, shows a variation of about 1.0 magnitude.

21 3.1. The spectrum of this star is similar to that of —47°6614, mag. 9.9, mentioned above, and *Z. C.* 18^h 1935, mag. 9. These three are the only stars, so far known, which have this spectrum.

22 19.9. A spectrum plate, taken with the eight-inch Draper Telescope on December 18, 1903, shows the spectrum of this faint gaseous nebula superposed on that of +50°3007, magnitude 9.4, which is of class A.

22 59.2. Found from comparison of chart plates. Measures of sixty-nine plates, taken between November 23, 1889, and January 19, 1901, show a variation in magnitude from 8.8 to 12.2.

In a photograph taken with the eight-inch Bache telescope on July 15, 1898, the variable star *RS Ophiuchi* has a spectrum of the third type in which the lines $H\zeta$, $H\epsilon$, $H\delta$, $H\gamma$, $H\beta$ are bright, the estimated relative intensities of these lines being about 2, 1, 5, 10, and 20, respectively. Two bright lines, intensities 7 and 14, are also present. They appear to coincide with the bright lines in γ *Velorum*, whose wave-lengths are 4656 and 4691. No other variable star having this type of spectrum has hitherto been found.

EDWARD C. PICKERING.

MARCH 21, 1904.

VARIABLE STARS IN THE NEBULA OF *ORION*.[1]

THE Great Nebula of *Orion* has been the subject of careful study by astronomers for many years. Volume 5 of the *Annals* of the Harvard Observatory contains an elaborate discussion of this nebula, by Professor Bond, including a comparison of the material previously collected. Many stars in it have been announced as variable, but strangely enough the changes in only one of them, *T Orionis*, have been generally admitted. In 1901, and again in 1903, Professor Wolf, of Heidelberg, compared several of his photographs by means of stereo-comparators and announced a number of variables in this part of the sky. They do not appear to have been confirmed by other observers, and final designations have not yet been assigned to them. The faintness of many of these stars even at maximum renders it probable that comparatively few photographs exist on which they can be followed. A grant made by the Carnegie Institution for 1903 permitted a large amount of work of this kind to be undertaken here, and furnished a corps of eight observers for the study of the Harvard photographs. The failure to continue this grant for 1904 rendered it necessary to disband this corps, and since December 1903 similar work has been carried on, at the expense of the observatory, by only one observer, Miss Henrietta S. Leavitt. A number of photographs of the nebula of *Orion*, having long exposures, are contained in the Harvard collection, and a careful examination of them has been made by Miss Leavitt. Besides confirming sixteen of Wolf's variables, she has found many new ones, which renders it probable that nebulæ as well as clusters may furnish fruitful fields for the discovery of such objects. Three plates taken with the thirteen-inch Boyden telescope were examined, the first made on September 15, 1893, exposure 180^m; the second on September 17 and 18,

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[1] *Harvard College Observatory Circular* No. 78.

1893, exposure 480^m; and the third on December 5, 1893, exposure 151^m. Plates taken with the twenty-four-inch Bruce telescope, on January 8, 1894, exposure 60^m; January 25, 1894, exposure 60^m; January 27, 1895, exposure 180^m; October 6, 1896, exposure 180^m; November 9, 1896, exposure 123^m; November 10, 1896, exposure 265^m; December 17, 1898, exposure 60^m; December 3, 1901, exposure 60^m; and December 4, 1901, exposure 420^m, were also used. For stars which, on plates having long exposures, are deeply involved in nebulosity, an examination was also made of plates taken with the thirteen-inch Boyden telescope on September 12, 1893, exposure 10^m, and on March 13, 1896, exposure 10^m, and of plates taken with the twenty-four-inch Bruce telescope on November 30, 1893, exposure 61^m; December 27, 1893, exposure 60^m; January 1, 1894, exposure 11^m; January 1, 1894, exposure 60^m; October 29, 1897, exposure 10^m; and December 8, 1898, exposure 10^m. Some excellent photographs taken with the eight-inch Bache telescope in 1888 (*Annals* **18**, 114) can be used only for the brighter variables. So far as possible, the map and catalogue of Bond (*Annals*, **5**) were used to locate these stars, and their positions were derived by adding the co-ordinates given by Bond to those of θ^1 *Orionis*, whose position for 1900 is assumed to be R.A. $= 5^h\ 30^m\ 21^s.3$, Dec. $= -5^\circ\ 27'.3$. Estimates were made of the positions of stars not in this catalogue, and are given to seconds of time in right ascension, and to tenths of a minute of arc in declination.

A provisional scale of magnitudes was used which is fairly comparable with that of Wolf. On this scale, the faintest stars seen on Plate 26 of Roberts's *Photographs of Stars, Star Clusters and Nebulæ* have the magnitude 14.8. The original negative was taken with his twenty-inch reflector on January 15, 1896, and had an exposure of 90 minutes. The faintest stars shown in Plate XXIII of Volume **2** of the *Publications of the Yerkes Observatory* have the magnitude 15.5. The original negative was taken with the twenty-four-inch reflector on October 19, 1901, and had an exposure of 60 minutes.

A list of the stars certainly variable is given in Table I. Those found by Wolf have been confirmed by Miss Leavitt. Those found by Miss Leavitt have been examined by Mrs. Fleming, on several plates, and the variability in each case confirmed. Although the changes in some of these stars are small, they seem to be real, since, owing to their faintness, good comparison stars can be found near them. A number for reference, the provisional designation given to Wolf's stars in the *Astronomische Nachrichten*, **163**, 161, the number in the catalogue of

TABLE I.

Stars Certainly Variable.

No.	Designation	Bond No.	R. A. 1900	Dec. 1900	HARVARD		HEIDELBERG	
					Br.	Ft.	Br.	Ft.
1	....	...	$5^{h}27^{m}$ 53^{s}.	$-5^{\circ}44'.0$	14.1	<15.5	....	....
2	....	...	28 27.	−5 26.1	14.5	<15.1	....	....
3	36.1903	...	28 37.	−5 16.1	14.4	14.9	13.8	15.0
4	....	...	28 37.	−4 47.6	14.0	15.0	....	....
5	....	173	28 37.0	−4 48.2	13.9	14.6	....	....
6	....	...	28 40.	−5 5.7	13.3	14.6	....	....
7	....	...	28 47.	−6 22.8	12.5	<15.5	....	....
8	....	...	28 54.	−6 44.3	13.2	15.5	....	....
9	....	...	28 59.	−5 45.8	13.2	14.1	....	....
10	37.1903	...	29 0.	−4 52.0	13.8	15.2	13.0	15.2
11	....	...	29 5.	−6 40.3	13.7	<15.5	....	....
12	....	276	29 8.7	−5 41.1	12.9	14.0	....	....
13	....	288	29 12.2	−5 17.8	12.9	14.2	....	....
14	....	...	29 15.	−4 54.1	14.5	15.2	....	....
15	....	...	29 21.	−5 8.6	14.3	<15.0	....	....
16	38.1903	...	29 24.	−6 40.0	11.4	14.1	13.0	15.0
17	....	...	29 29.	−5 35.0	13.5	14.8	....	....
18	....	...	29 31.	−4 49.5	14.9	15.5	....	....
19	....	417	29 42.8	−6 9.6	13.4	14.5	....	....
20	....	419	29 43.0	−5 39.0	14.1	14.6	....	....
21	....	435	29 46.0	−5 26.8	12.1	12.7	....	....
22	....	...	29 47.	−5 50.1	14.2	15.5	....	....
23	....	...	29 49.	−5 14.8	14.2	15.5	....	....
24	....	481	29 54.8	−6 2.0	11.8	12.8	....	....
25	39.1903	484	29 55.1	−4 44.2	14.0	14.6	12.5	14.0
26	40.1903	509	30 1.6	−5 50.6	13.2	13.9	12.5	14.0
27	....	511	30 2.1	−5 45.7	13.4	14.0	....	....
28	....	...	30 2.5	−6 27.9	13.1	14.0	....	....
29	....	520	30 4.3	−5 58.6	14.1	14.9	....	....
30	....	...	30 5.	−4 54.8	12.7	13.1	....	....
31	....	...	30 12.	−5 40.3	12.9	14.7	....	....
32	....	561	30 12.2	−4 31.7	12.2	14.6	....	....
33	....	...	30 13.	−5 41.1	14.1	15.0	....	...
34	41.1903	582	30 16.3	−5 50.5	12.1	13.0	12.0	14.5
35	42.1903	596	30 18.2	−4 49.7	13.0	13.7	12.7	<14
36	....	606	30 19.5	−5 47.2	12.7	13.7	...	....
37	....	620	30 20.7	−5 43.2	12.7	13.1	....	....
38	....	...	30 21.	−5 56.1	13.8	14.6	....	....
39	....	...	30 24.	−4 57.8	14.2	14.9	....	....
40	....	668	30 25.5	−4 46.2	12.4	13.0	....	....
41	43.1903	680	30 26.8	−5 38.6	12.9	14.0	12.3	<14
42	....	695	30 30.1	−5 13.7	11.1	12.5	....	....
43	....	703	30 31.0	−5 15.0	11.8	13.2	....	....
44	....	709	30 31.5	−5 29.6	10.7	11.3	....	....
45	....	...	30 34.	−4 59.1	13.2	14.3	....	....
46	83.1901	756	30 40.0	−5 5.1	11.6	14.2	11.8	13.2
47	50.1903	758	30 40.1	−6 49.2	13.4	14.6	12.5	<14
48	....	759	30 40.3	−5 25.5	13.0	13.6	....	....
49	....	784	30 47.2	−5 32.1	10.3	11.0	....	....

TABLE I — *Continued.*

No.	Designation	Bond No.	R. A. 1900	Dec. 1900	HARVARD		HEIDELBERG	
					Br.	Ft.	Br.	Ft.
50	....	788	$5^h 30^m 47^s.3$	$-5^{\circ}\ 9'.7$	14.0	<15.2	....	....
51	....	...	30 52.	−5 5.1	14.4	15.0	....	....
52	....	817	30 54.0	−5 53.5	14.1	14.8	....	....
53	....	822	30 55.6	−5 32.4	....	....	....	....
54	44.1903	...	30 57.	−4 51.1	13.3	<15.0	12.8	<15
55	....	838	30 58.1	−5 8.0	12.3	13.3	....	....
56	....	...	31 0.	−6 25.5	14.1	14.7	....	....
57	45.1903	...	31 1.	−6 54.8	14.5	15.4	12.5	15.0
58	....	...	31 9.	−4 45.5	14.0	14.8	....	....
59	46.1903	877	31 9.2	−6 46.5	13.0	14.9	12.6	<14
60	....	885	31 13.8	−6 18.2	12.8	13.9	....	....
61	....	...	31 16.	−6 52.0	14.4	<15.4	....	....
62	....	...	31 18.	−6 33.3	13.7	<15.0	....	....
63	85.1901	908	31 21.4	−5 15.4	11.5	12.1	11.8	<14
64	....	...	31 28.	−6 21.5	13.0	14.5	....	....
65	....	951	31 42.7	−5 29.9	13.5	14.6	....	....
66	....	...	31 46.	−6 23.1	12.1	13.3	....	....
67	....	1009	32 8.8	−6 37.1	11.5	<14.8	....	....
68	....	...	33 3.	−7 1.2	13.7	14.4	....	....
69	86.1901	...	34 46.1	−3 28.6	13.5	14.4	11.7	13.0
70	....	...	35 13.	−6 18.9	12.2	13.2	....	....
71	49.1903	...	36 36.0	−4 11.3	10.5	<14.8	9.8	<15

Bond, the right ascension for 1900, and the declination for 1900 are given in the first five columns. The brightest and faintest magnitudes on the Harvard and Heidelberg photographs are given in the next four columns.

REMARKS.

3. Although the observed range is small, the variation is very clearly marked.

4, 5. The variation of these adjacent stars is marked.

6. Period apparently short.

12. Period apparently short.

13. Period apparently short.

18. This star, although faint, gives distinct images on the plates, and the variation is well defined.

20. The variation of this star, though small, is well shown by a comparison with three neighboring stars of about magnitude 14.5.

28. Bond 528 and Bond 537, the stars nearest this position, are wrongly charted on Bond's map. The position has, therefore, been determined independently.

30. The variation is obvious when different photographs are compared, but the strong nebulosity in the region of this star makes measurements of the magnitudes difficult.

37. The variation is small, but readily observed, as the variable is sometimes brighter and sometimes fainter than Bond 605, which precedes it $1^s.2$, and is in the same declination.

44. This star was suspected of variability by Holden.
47. Wolf announced this star as probably variable.
49. This star was suspected of variability by Schmidt.
51. Although this is a faint variable, it is easily observed. A star of about the fifteenth magnitude follows and is slightly south of it.
53. *T Orionis.* This star was not measured, but the variation is obvious, on the plates examined.
63. No marked variation was found in this star, which was observed with some difficulty.
64. This star is on Bond's chart, but not in the catalogue.
66. This star is on Bond's chart, but not in the catalogue.
68. This star precedes the position given by Wolf of 47.1903, 35^s, and is north of it 18′.
70. This star precedes the position given by Wolf of 53.1903, 26^s, and is north of it 10′.

A list of stars suspected of variability is given in Table II, in the same form as Table I, omitting the last four columns. All of Wolf's stars may prove to be variable, but some are included in Table II, since they have not yet been confirmed here.

TABLE II.

Suspected Variables.

No.	Designation	Bond No.	R. A. 1900	Dec. 1900	No.	Designation	Bond No.	R. A. 1900	Dec. 1900
1	80.1901	...	$5^h24^m47^s.0$	−8° 5′.2	19	....	...	$5^h30^m37^s$	−4°52′.8
2	32.1903	...	26 59.2	−4 31.4	20	....	801	30 51.0	−5 32.0
3	33.1903	...	27 13.6	−5 7.1	21	....	833	30 57.3	−5 55.6
4	34.1903	...	27 16.6	−7 32.8	22	....	...	30 59.	−5 30.3
5	35.1903	...	27 54.0	−7 38.8	23	84.1901	...	31 0.4	−5 0.8
6	....	216	28 50.5	−5 35.3	24	....	...	31 5.	−6 1.3
7	81.1901	...	28 54.0	−4 42.8	25	....	...	31 37.	−5 20.8
8	....	...	29 15.	−5 36.3	26	51.1903	...	32 18.4	−3 35.2
9	....	361	29 29.1	−5 1.1	27	....	...	33 3.	−4 16.8
10	....	492	29 56.8	−5 7.5	28	47.1903	...	33 38.4	−7 19.2
11	....	...	30 0.	−6 33.5	29	52.1903	...	34 31.9	−4 57.4
12	....	524	30 5.2	−5 27.0	30	87.1901	...	35 10.1	−5 24.4
13	....	527	30 5.6	−5 48.5	31	53.1903	...	35 39.4	−6 29.0
14	....	558	30 10.7	−5 29.3	32	48.1903	...	35 57.8	−8 8.5
15	....	...	30 14.	−5 35.5	33	54.1903	...	35 57.9	−8 7.7
16	....	...	30 17.	−5 34.5	34	88.1901	...	42 27.9	−6 14.8
17	....	...	30 25.	−5 35.3	35	89.1901	...	43 16.1	−5 43.6
18	82.1901	...	30 36.8	−6 7.1					

REMARKS.

1. The region is on the extreme edge of the plates examined. No variation was detected in any star near the position announced.
2. No star near this position was found to vary with certainty. A fourteenth magnitude star was suspected of being unduly faint on January 8, 1894, and on January 27, 1895.

3. No variation could be found in any star near this position. Probably the variable remains faint during the greater part of the time, as it was seen bright on only one of the Heidelberg plates.
4. A star of about the magnitude 14.5 in this position appears to fluctuate slightly in brightness, but no conclusive evidence of variation has been found.
5. No variation was found in any star near this position.
7. Assumed to be Bond 223. On the plates examined the star is always of about the magnitude 13.5. No star near this position has been found to show variation.
14. This star is in a strongly nebulous region and the variation is possibly only apparent.
18. The star nearest the position is Bond 745, which does not show variation on the plates examined. On each of them it is of about the magnitude 13.5.
20. Bond considered this star to be variable. There appears to be some fluctuation in light, but on the plates examined the evidence of variability is not conclusive.
23. Bond 844 is in the position given. On all the plates examined, the light remains at about the magnitude 13.7.
26. No variation was found in any star near the position given.
28. A star near this position appeared to be nearly half a magnitude fainter than usual on December 17, 1898. The images of stars in the vicinity are poor, however, and the evidence of variation does not appear to be conclusive. See remark on No. 68 in Table I.
29. The star nearest the position given shows some evidence of variation. On the plates the brightness appears to be constant. On January 8, 1894, and January 27, 1895, the star appears nearly half a magnitude fainter than usual, but the images are poor in each case.
30. Of the two stars near this position, the southern always appears about two-tenths of a magnitude the brighter, except on the plates taken November 9, 1896, and December 3, 1901. On these plates the two stars appear equal.
31. No star near the position given shows variation on the plates examined. See remark on No. 70 in Table I.
32. The region is covered by only three of the plates examined, and on them the star is too near the edge for accurate observation. The northern of two faint stars near this position was suspected of being half a magnitude brighter on November 10, 1896, than on November 9, 1896. The two stars are doubtless Wolf's 48.1903 and 54.1903.
33. See remark on No. 32.
34. The region is on the edge of the plates examined. No star could be found showing the progressive diminution of light announced by Wolf.
35. The region is on the extreme edge of the plates examined. No star near the position was found to show variation.

The region covered in this examination was that of Bond's map, which extends between the limits preceding and following θ^1 *Orionis* by $2^m 42^s$, and from $87'$ north of this star to $91'.5$ south of it. The corresponding limits for 1900 are R. A., $5^h 27^m.7$ to $5^h 33^m.1$, Dec., $-4° 0'$ to $-6° 59'$. The area of this region is 14,458 square minutes of arc, and the number of stars examined about 3,000. A small region near the announced position of each of Wolf's variables, situated beyond the limits of the map, was also examined.

The distribution of the variables contained in Table I emphasizes their close connection with the nebula. They are found principally in a narrow region on each side of a line extending southward from c *Orionis* through θ and ι, and beyond. North of declination $-4^\circ 44'$ only one variable was found out of about 900 stars examined. Within the limits of the remainder of Bond's map, out of 550 stars examined, only one variable has been found preceding R. A. $5^h\,28^m.4$, and out of 450 stars examined, only one variable has been found following R. A. $5^h\,31^m.8$. The areas of these three regions are 3524, 1417, and 2632 square minutes of arc, respectively. In the remaining region, covering 6885 square minutes, out of about 1,100 stars examined, 65 have been found to be certainly variable, and 20 more are probably variable. A suspicion is also attached to several other stars not here announced.

It is not improbable that other variables may be discovered when more photographs become available for comparison, as many of those found appear to be of the same class as the variables in globular clusters which remain at their minimum magnitude during a large part of the time. Those of Wolf's variables which were not confirmed upon the Harvard plates may belong to this class.

EDWARD C. PICKERING.

MARCH 23, 1904.

REVIEWS

Handbuch der Spectroscopie. Von H. KAYSER. Zweiter Band. Leipzig: S. Hirzel, 1902.

THE very exceptional interest and importance of the second volume of Kayser's great *Handbuch* seemed to call for an extended critical review, which might do the book some measure of justice. Unfortunately, the pressure of other duties has left insufficient opportunity for such a task, and the passage of time gives warning that another volume may be forthcoming before mention has been made of its predecessor. For this reason it seems preferable to publish even an inadequate reference to the present volume now, rather than to wait longer for a better opportunity. So far as the importance of the book goes, it is quite unnecessary to speak. Every spectroscopist knows that here is the one source in which he may find a full and critical discussion of the literature of his subject. Not only does this include references to practically every work of importance, but we also find a careful summary of the results of each research, in which all important points are brought out and accompanied by critical remarks from one of the best living authorities on spectroscopic subjects. Professor Kayser rarely fails to discover the weak point of a paper, whether it be in the methods of observation or in the discussion of the results. At times he is perhaps a severe critic, but his criticisms are based upon sound and careful reasoning, and almost invariably command the reader's approval.

The first volume of the *Handbuch*, with its admirable description and critical account of spectroscopic instruments, has doubtless been a chief book of reference to all spectroscopists since the time of its appearance. The second volume deals with a wide range of subjects, and is even more fascinating than the first. Here we find chapters on emission and absorption, the radiation of solid bodies, the radiation of gases, the spectra of compounds and multiple spectra, the influence of temperature, pressure, and the nature of the electric discharge on spectra, the widening and reversal of spectra lines, Doppler's principle, spectral series, and radiation in the magnetic field. The chapter on Doppler's principle is by Professor Kayser's assistant, Dr. H. Konen, while that on the Zeeman effect is by Professor Runge. It would be an agreeable task to analyze carefully the contents of the book, and to discuss many of the interesting questions which it raises; but we must content ourselves with a few remarks on certain points which seem to call for special mention. It ought to be said that these are taken more or less at random, and by no means cover the most important portions of the book.

At the present time few subjects in spectroscopy are of greater interest than the applicability of Kirchhoff's law to the solution of solar and stellar problems. The law requires that the radiation must be due to heat alone, and when this condition is not met, conclusions based upon the law may be invalid. We find many cases to which it seems impossible to apply the law directly, *e. g.*, that of the calcium vapor in the flocculi, which appears to increase in radiating power as it rises above the photosphere, until it attains a maximum at some point below the upper limits of the chromosphere. Hydrogen in the flocculi offers another most interesting case, in which one is tempted to believe at least that the law is sufficiently obeyed to permit the conclusion that the bright hydrogen flocculi are actually hotter than the dark ones. But if mystery still attaches to such phenomena, it must not be forgotten that the law seems to be capable of explaining certain appearances, such as the simultaneous presence of dark and bright hydrogen lines in the spectrum of a star, which have sufficed to puzzle able observers. This point, together with many others of equal interest, is discussed by Professor Kayser in the first chapter of his volume, which contains Kirchhoff's original statement of the law in slightly modified form, together with both qualitative and quantitative proofs of the law and Paschen's quantitative proof for gases. To the astrophysicist the summary in the second chapter of the remarkable recent advances, both experimental and theoretical, in our knowledge of the radiation of solid bodies will be of special importance in connection with the determination of the Sun's temperature. The extravagant values of the solar temperature reached by early investigators were due almost entirely to the use of incorrect radiation formulæ, and recent determinations, based upon more reliable formulæ, agree far better among themselves. The work described in this chapter, and also, indeed, in every other chapter of the book, affords striking illustration of the dependence of the astrophysicist upon the experimental and theoretical investigations of the physicist, with whose work he cannot be too familiar. From an experimental standpoint, one of the most important advances of recent years has been the realization in the laboratory of a perfectly black body. This principle has already found practical application in the construction of bolometers, as well as in other departments of investigation.

The chapter on the radiation of gases opens with a confession of our almost total ignorance of the source of the energy which constitutes light, and the nature of the transformation of this energy into light. It is an excellent plan to bear constantly in mind, as Professor Kayser insists that his readers shall do, that the nature of the discharge in vacuum tubes and in the spark, for example, is almost wholly unknown; whence the danger must be obvious of applying conclusions based upon the study of these phenomena in the explanation of other and even more mysterious phenomena. Kayser believes, as Rowland was inclined to do, that the phenomena of the electric arc are to be regarded as more truly thermal than electrical, while the complex phenomena of the spark are to be considered as involving less of distinctly thermal influence. Rowland's almost exclusive use of the arc in his spectroscopic work was due to a desire to avoid the complications inevitable when the high potential discharge is employed. Kayser also gives the necessary weight to radiation resulting from chemical processes, and to the phenomena of fluorescence and phosphorescence. It is interesting to note that, while Kayser believes that a considerable part of the energy emitted by flames is the direct result of chemical processes, he nevertheless thinks that the spectra of all gases could be produced by heat alone, if sufficiently high temperatures were available. This is a point of special interest, since it is constantly appearing in discussions of solar and stellar phenomena.

Chapter IV contains an extended critical discussion of Lockyer's dissociation hypothesis, in which both the weak and the strong points in Lockyer's arguments are clearly pointed out. After quoting Schuster's views, Kayser expresses his conviction "that in general the spectrum of an element is compounded of numerous spectra, which belong to variously constructed molecules: the majority of the molecules will correspond to the degree of dissociation given by various controlling conditions at the time—temperature, pressure, quantity of dissociated and undissociated molecules, manner of excitation. But we always have a number of molecules which correspond to greater and less degrees of dissociation, the number of which diminishes the farther they are from the mean condition. For each substance there is a definite temperature at which it is completely dissociated, and this condition will be the more easily reached the simpler the molecule and the lower its melting-point." It will thus be seen that Kayser shares Lockyer's general views, though he does not follow him in many of his conclusions. He is ready to accept the view that at very high temperatures the elements may be broken up into parts which give different spectra, but he refuses to follow Lockyer when he contends that these constituent parts are common to different elements.

It would be interesting to examine Kayser's discussion of the various arguments advanced by Lockyer in favor of the dissociation hypothesis. Kayser points out the weakness or total failure of the arguments based on the supposed absence of metalloids from the Sun; the supposed existence of lines common to two or more elements ("basic lines"); the faulty interpretation of experiments involving the distillation of magnesium and other vapors; the assumption that certain carbon bands may appear alone, and mark different degrees of dissociation, whereas they in reality are due to cyanogen, and always appear together; the assumption that hydrogen given off by heating such elements as sodium and lithium is due to dissociation, when in fact it is simply occluded gas. He is inclined to attach more weight, however, to the variation of the intensity of the 4227 and H and K lines of calcium under different conditions, though he is careful to refer to the effects obtained by Huggins in varying the density of the calcium vapor. Kayser seems to think Lockyer's strongest arguments are those derived from his studies of solar and stellar spectra, and remarks that at these very high temperatures dissociation would be much more probable. In this connection he discusses the question of basic lines in spots and prominences, the different distortion of different lines of the same element (which Kayser considers as a proof of dissociation), the change of the widened lines in spots during the transition from the maximum to the minimum period, and the question of enhanced lines in the spectra of stars and the chromosphere. The fact that different lines of the same element are not always similarly affected in solar eruptions is exceedingly important, but it would be well to reserve conclusions until this question has been given a thorough investigation with modern instruments. The same may be said of the question of widened lines in Sun-spots, since Lockyer's plan of recording only a few of the most widened lines, with instruments not sufficiently powerful to remove all doubts as to identification, is undeniably faulty. As for enhanced lines in stellar spectra, some of Lockyer's recent results are certainly most interesting and suggestive, but here again an important difficulty remains through the possible confusion of electrical effects with those of temperature alone. In spite of the apparent evidence in favor of dissociation, resulting from recent investigations of the Zeeman effect; the effect of pressure on wave-length; the existence of the second series of hydrogen in certain stars; the different behavior of different lines of the same element under change of self-induction; the apparently different velocities corresponding to different lines of the same element, as observed by Schuster in measuring the speed of the particles shot off from the poles in an electric discharge; the experiments of Thomson on the breaking up of the hydrogen atom; and the emission of helium by radium; it is probable that many spectroscopists will prefer to reserve judgment for the present, even though they may be inclined to believe that dissociation offers the simplest means of explaining a large number of phenomena.

Chapter v, on the influence of pressure, temperature, and the nature of the electric discharge on spectra, is an exceedingly interesting discussion of the literature of these subjects. Chapter vi deals with the widening of spectral lines, and with single and multiple reversals. Chapter vii gives an excellent account of Doppler's principle, dwelling, however, upon the physical elements of the problem, and referring only briefly to its astronomical applications. Chapter viii is a most valuable account of the subject of spectral series, including all of the exceedingly important work done in this field during recent years. The volume concludes with Professor Runge's chapter on radiation in a magnetic field, which constitutes the most valuable discussion of this subject hitherto published.

Even from this brief mention of some of the principal contents of the volume, it will be seen that the work of every spectroscopist must be greatly facilitated by having the book constantly at hand. The suggestions as to problems which still require investigation are most valuable, and may be especially commended to those who are seeking subjects for research. When the five volumes of the *Handbuch* have been completed, they will form a library of spectroscopy the importance of which it would be difficult to overrate.

G. E. H.

Light Waves and Their Uses. By A. A. MICHELSON, The University of Chicago Press, 1903. Pp. 166, with 108 figures in text and three colored plates. Price, $2, *net.*

THE title of this book, taken in conjunction with the name of its author, leads one to suppose, even before reading it, that it deals mainly with interference phenomena, and particularly with the many interesting applications of the interferometer. The author apologizes for describing so many of his own experiments, offering the very satisfactory excuse that he is more likely to make the subject interesting by doing so than by giving accounts of the work of others.

The book is based on eight lectures given at the Lowell Institute in Boston in 1899. Probably the most serious criticism that can be brought against it is that many of the more elementary explanations and definitions are too brief to be readily understood by the general reader, for whom they were intended. This is the case with such concepts as "phase," "simple harmonic motion," etc. The transition from the telescope or microscope to the interferometer is also rather confusing, and indeed it is hard to see that anything is gained by such a conception of essential similarity in instruments so unlike.

Apart from a few such matters, there is little to criticise and much to commend; and the hope expressed in the preface, that "some of the ideas may be of interest to physicists and astronomers," proves to be well founded.

The first lecture deals with the wave theory of light, and particularly with interference phenomena, the colors of thin films, and the lengths of the waves for different colors. The second treats of diffraction through openings of different shapes, and the resolving power of telescopes and microscopes, and introduces the interferometer.

In Lecture III the corpuscular theory is spoken of, and the crucial question of the relation between the velocity of light in air and that in a denser medium, as well as the solution of this question by the determination of both velocities in the laboratory. This brings up the subject of refractive indices, for the determination of which the interferometer is particularly suitable. Other applications are given, such as the determination of coefficients of thermal expansion, the testing of precision screws, and the measurement of wave-lengths.

Lecture IV is concerned chiefly with the method of visibility curves, as applied to the analysis of spectral lines which are usually considered monochromatic. Incidentally a short but interesting account of the harmonic analyzer is given.

Lecture V is devoted entirely to the measurement of the standard meter in terms of the wave-lengths of cadmium lines, and this is one of the most interesting parts of the book.

Lecture VI starts out with the Zeeman effect and the results obtained with the interferometer, using the visibility curve method.

In the latter half there is given an elementary explanation of grating spectra, and the limitations of the grating which led to the invention of the echelon spectroscope. Many will disagree with the statement on page 126 that the latter has all the advantages of the grating in addition to greater resolving power.

Lecture VII is on the application of interference methods to astronomy, particularly the increase of resolving power obtained by putting a pair of movable slits over the objective, or a movable system of mirrors. The principal applications are to close double stars and very small disks, as of asteroids or satellites; but the possibility of determining the diameters of fixed stars is also claimed.

The last lecture, under the title "The Ether," deals principally with the aberration problem, and the experiments carried out by Fizeau and by Michelson and others to explain the observed anomalies.

Altogether this book is of great interest to many besides the general reader, particularly as it gives a clear résumé of researches where in some cases the original papers are not readily accessible.

H. M. R.

Wellenlängen-Tabellen für spektralanalytische Untersuchungen, auf Grund der ultravioletten Funkenspektren der Elemente. Von Franz Exner und E. Haschek. Theil I, pp. 83; Theil II, pp. 269. Leipzig und Wien: Franz Deuticke, 1902. 16 Marks.

Ten years ago the complaint could justly be made that the measurements of celestial spectra had been carried to a higher degree of precision than those upon spectra observable in the laboratory. This deficiency has been gradually remedied during recent years, so that the advance can be pushed in the quantitative work on the spectra of celestial bodies, which work must obviously depend upon the foundations established in the laboratory. Each additional table of wave-lengths accurately determined is to be welcomed, and with the acknowledged limitations of present methods of spectroscopic research there seems little danger of waste of effort in the duplication of measurements of wave-lengths of the lines of the elements, as produced under different conditions in the arc, spark, or other source.

The present tables differ from other contemporaneous measurements chiefly in the manner in which they were obtained. The authors employ the objective method of projecting upon a scale on a screen an image of the negative, which was taken with a Rowland concave grating (of 15 feet radius, with 20,000 lines to the inch). A description of the method has already been given by Dr. Karl Kostersitz in this JOURNAL.[1] Wave-lengths are read off (only a single reading was made) directly on the scale, which is adjusted to its proper position with the aid of standard comparison lines of iron photographed immediately after the exposure of the element under investigation. Sufficient testimony as to the convenience and rapidity of this procedure is given by the fact that these tables, comprising the violet spark spectra of practically *all* of the elements, were produced in less than two years. Rowland's wave-lengths were used for the standard lines.

The authors devote some space in their introduction to a discussion of the accuracy of measurement attained by them in this work, and they conclude that the method stands on an equality in this respect with the usual process of measuring with a comparator and microscope. This will doubtless be questioned. The errors due to optical distortion in the projection apparatus are likely to be more serious than in case of a comparator, where the settings are commonly made at the same central point in the field. It is, furthermore, obvious that the defects in the definition of the lines on the negative, whether due to improper exposure or poor focus, will have their effect on the reading quite as seriously as in case of the comparator, and the advantage is lost of the repetition of the settings, unprejudiced by a knowledge of the reading on the micrometer head. The authors contented themselves with an accuracy averaging about 0.015 tenth-meters, considering it undesirable to go beyond this on account of the "shifts" which they observed in the case of many lines. A criticism of the reality of these supposed displacements by Messrs. Eder and Valenta appears elsewhere in this number, and will doubtless tend to diminish the reader's confidence in the accuracy of these wave-lengths of Messrs. Exner and Haschek. However, even if the precision of the results in these tables may be considerably less than the authors have estimated, their value to the physicist, chemist, and astronomer is nevertheless great, on account of their comprehensiveness, convenience of arrangement, and compactness.

The tables are comprised in three parts: (1) a list of the principal spark lines of each of the elements, which are arranged in alphabetical order, with estimates of the intensities of the lines (for iron thirty-five such lines are given); (2) a list, in order of wave-length, of the chief lines of all the elements, with the symbol of the element in which a line is found. This should be of service where it is desired to trace the origin of a conspicuous line, or to find what element will produce a line near a desired wave-length. This list occupies fifty-two pages, but in practice is likely to be found too incomplete rather than too full. (3) The complete list, for the region covered, from about λ 2100 to 4700, of the measured wave-lengths of all the spark lines observed by the authors, arranged by elements in alphabetical order. This constitutes *Theil II* of the work. References are given under each element to the other recent measurements by other investigators.

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[1] **16,** 262–264, November 1902.

The tables are printed in large, clear type without waste space, on a page 18 × 12 cm in size. They will assuredly serve a useful purpose, even if the individual wave-lengths are not accepted as up to the standard of the highest accuracy now attainable. E. B. F.

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ON A POSSIBLE VARIATION OF THE SOLAR RADIATION AND ITS PROBABLE EFFECT ON TERRESTRIAL TEMPERATURES.[1]

By S. P. LANGLEY.

INTRODUCTION.

THE purpose of the present communication is primarily to discuss the validity of a surmise we may entertain, founded on observations here, as to certain possible changes in the solar constant. There is especially discussed a possible falling off of solar radiation about the close of March 1903, as indicated by certain recent values of solar radiation computed from observations here, and compared with actually observed temperatures for eighty-nine stations of the North Temperate Zone.

I. METHODS OF OBSERVATION AND CONSIDERATIONS GOVERNING THE ADMISSION OR REJECTION OF EXPERIMENTAL DATA.

The determination of the solar radiation toward the Earth, as it might be measured outside the Earth's atmosphere (called the "solar constant"), would be a comparatively easy task, were it not for the almost insuperable difficulties introduced by the actual existence of such an atmosphere, above which we cannot rise, though we may attempt to calculate what would be the result if we could. The determinations of the so-called solar constant, then, chiefly depend on various methods of eliminating the effects of the terrestrial atmospheric absorption, since only after the actual interposition of this we receive the Sun's heat.

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[1] Reference may be made to the writer's paper in the ASTROPHYSICAL JOURNAL for March 1903, and to Mr. C. G. ABBOT'S paper in *Smithsonian Miscellaneous Collections* (Quarterly Issue), **45**, 74–83, 1903.

These determinations depend principally on two classes of observations:

First, on getting as far above this atmosphere as possible, by the actual ascent of a lofty mountain, and by the observation of the solar radiation there with a subsequent comparison with that nearer its base. This method possesses great advantages over any other, but presents obvious difficulties in the execution.[1]

The second principal class of observations, and the only one considered here, is restricted to a single station, which we must usually take in a low altitude like that at Washington. It consists in making measurements (1) by the actinometer, of the total radiation observed; (2) of the intensity of homogeneous rays in different parts of the solar spectrum for different altitudes of the Sun. (3) From these direct observations we can in theory calculate the total absorption of the atmosphere from the evidence gathered by the spectrobolometer as to that of the several rays for different altitudes of the Sun and for different thicknesses of air.

As our atmosphere and its absorption is in a condition of incessant fluctuation, it will always be hard to discriminate between changes due to it and those, if any, due to an actual change in the radiation of the Sun itself; and this discrimination constitutes the particular difficulty of the present research.

The present discussion will lead us to estimate the validity of any surmise as to the actual changes in the solar constant, founded on such observations as those of the second class.

As for the accuracy of the actinometer measures of total solar radiation at the Earth's surface, it is easy to obtain measures relatively exact, within about 2 per cent., or perhaps even less.

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[1] For an example of it the reader is referred to the account of the writer's expedition to Mount Whitney, *Professional Papers*, U. S. Signal Service, No. XV.

But the absolute standardization of the instrument offers uncertainty of quite another order, so that I do not think that the absolute magnitudes of the results to be presented here are necessarily within 20 per cent. of the truth, or even more.

The homogeneous rays are observed here by the bolometer, and the bolographic curves from which the atmospheric extinction of radiation is inferred, traced by the movement of the spot of light upon the galvanometer scale, are now very much more satisfactory than formerly. They represent an immense gain over the conditions operating when I began the work at Allegheny. The light-spot should move only by an impulse from the Sun, but, owing to extraneous causes, it was at first frequently impossible to keep it upon the scale of the galvanometer during so short a time as a single minute. The apparatus now, however, operates so well that such drift and tremor is relatively unknown, and the zero of the galvanometer is found almost unchanged for weeks together—a gain due to many causes and successive improvements during many years, from my own and other hands, but to which none have contributed more than Mr. Abbot, of this Observatory. Measurement and reduction of a series of from five to ten bolographs of a single day requires, however, so much labor that a single computation of the solar constant takes about one week.

It is of course the third branch of the inquiry, namely, the calculation of total atmospheric absorption from the bolometric measures, which offers the chief, and perhaps insurmountable, uncertainty. The measures on the extinction of homogeneous rays are assumed to be expressed by a logarithmic formula as follows:

$$\log d = m \log a + \text{constant} \ ,$$

in which d is the ordinate of the bolographic energy-curve corrected for instrumental absorption, m the air mass (proportional to the secant of the zenith distance of the Sun for moderate inclinations), and a the assumed transmission of the atmosphere for vertical incidence. If a is constant during the period of observation, the expression is in the form of the equation of a straight line, the tangent of whose inclination is $\log a$. Accordingly the measures of a single day, for separate wave-lengths, are plotted[1] with log d as ordinates, and m as abscissæ, and from these plots the values of a are determined. The logarithmic formula is itself immediately derived from the exponential formula of Bouguer, which, for constant barometric pressure and homogeneous rays, may be written

$$e = e_0 a^m ,$$

where e is the energy of the ray observed at the Earth's surface, e_0 its energy outside the atmosphere. Since d, the corresponding ordinate of the bolographic curve, is proportional to the energy of the ray, we may write

$$d = d_0 a^m , \quad \text{and } d_0 = \frac{d}{a^m} ,$$

where d_0 is the ordinate of the bolographic curve corrected for atmospheric transmission.

Thus assuming that we know a, and knowing m, we may immediately determine corrected ordinates representing the bolographic curve outside the atmosphere. The total area under such a curve is proportional to the total energy of all wave-lengths, so that the ratio of the area of the curve outside the atmosphere to the area of the curve at the Earth's surface is the correcting factor to be applied to the solar radiation as observed at the surface of the Earth, to give the value of solar radiation outside the atmosphere.

As remarked by the writer at p. 147 of the Report of the Mount Whitney Expedition:

> *If the absorption were invariable at all hours of the day and for all parts of the Earth situated at the same height above the sea and subjected to the same air-pressure*, the comparison of high and low Sun observations would give us the true energy outside the air, whether the absorbent material were distributed uniformly throughout the atmosphere or were gathered into horizontal layers superposed according to any law whatever. The character of the atmosphere interposed between us and the Sun, however, is constantly varying through the day, and even if it were at rest, a vertical section would have a different composition from that made at a very great inclination, which would necessarily pass over portions of the Earth's surface subjected to conditions very different from those existing at the place of observation.

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[1] The plots here shown are borrowed from the *Smithsonian Miscellaneous Collections*.

These observations apply to the methods of reduction now employed, but owing to the increased accuracy of observation, due to the great improvements of apparatus, and especially to the writer's introduction of the automatic or so-called bolographic recording devices, it is no longer necessary to follow the Sun very long or to very great zenith distances to obtain differences of ordinates of the bolographs measurable with sufficient exactness. The determinations are now chiefly made between the hours of 1 and 4 P. M., and it is only the air which transmits the rays during this interval whose uniform transparency is in question. While the atmosphere extends to an indefinite elevation, the portions within a few miles of the Earth's surface contain almost all the variable constituents of it, and the path of the ray in these lower layers does not sweep over a very large extent of the Earth's surface between the hours of 1 and 4 P. M.

The following table, computed for the times of the equinoxes, gives the areas of the Earth's surface over which the lower air-layers must remain unaltered in transparency during the observations, if good results are to be obtained:

Area over which Constant Transparency is Required	In the Air-Layer below an Elevation of
0.03 sq. miles	1 5 mile
0.86 "	1 "
3.0 "	2 "
6.8 "	3 "
12.1 "	4 "
304.0 "	20 "

As nearly all the clouds, water vapor, and other variable constituents of the atmosphere are contained in the layers below a two-mile elevation, it is immediately seen that the region over which approximately constant conditions must, for good observations, continue for three hours is not many square miles, and this is a demand which can ordinarily be approximately met.

Nevertheless, it is obvious that if there was no criterion as to whether constant conditions had prevailed during the measurements, the mere smallness of the period of time and of the area concerned would be of little weight for inference of the value of the resulting solar constant.

There are various kinds of evidence to be derived from the measures themselves, which aid in forming a judgment of their value for determining the constant, and enable us to reject certain days' observations which the impressions of the eye alone as to the clearness of the air might have inclined us to retain. These evidences are principally as follows:

1. The bolographic measurements of a single day on homogeneous rays, when plotted logarithmically, as already described, should be represented closely by straight lines, if the air and instrumental conditions are nearly invariable. Examples of good results of this kind are shown in the accompanying figure, which gives for March 25 and 26, 1903, the observations and representative lines for wave-lengths 1.027μ, 0.656μ, 0.468μ, and 0.395μ.[1]

2. The area of the (calculated) spectrum energy-curve outside the atmosphere ought to be nearly the same whether estimated from one or another bolograph of a given date. As examples of this and the two following criteria, the reader is invited to consult the table of solar constant values on a later page.

3. The several solar-constant values computed for a given date ought to agree within the limits of experimental error, though depending on independent bolographs and pyrheliometer measures.

4. If no variation of solar radiation occurs over several months, all the values of the solar constant computed during that interval should agree within close limits, regardless of alterations in the transparency of the atmosphere and the altitude of the Sun which may have intervened. In this connection the reader's attention is invited to the values of August, October, and December 1903.

5. As the great bands of the infra-red are presumed to be

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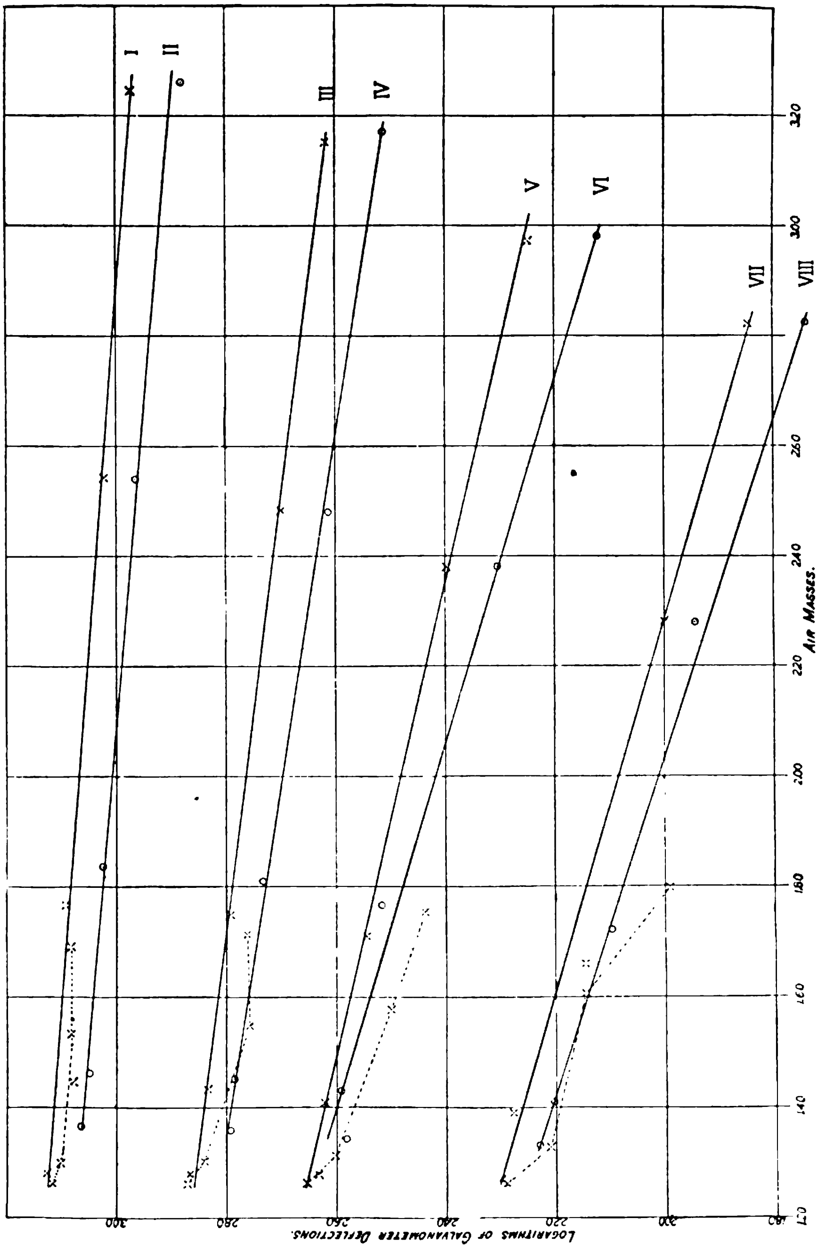
[1] The dotted portions of the lines of March 26 are for morning observations. As it is seldom found that the morning observations bear this test of uniformity of conditions of the atmosphere, they are now omitted, and the transmission coefficients are based on the afternoon bolographs alone.



TRANSPARENCY OF THE ATMOSPHERE FROM BOLOGRAPHIC OBSERVATIONS.

FIG. 1.

solely atmospheric, they should disappear in the energy-curve outside the atmosphere. Accordingly, the same result should be reached by the extrapolation in these regions, whether we determine a transmission coefficient at the bottom of the bands themselves, or from the smoothed curve above them. It appears from studies of Mr. Fowle, of the Astrophysical Observatory, that such is the case, except for the very deepest bands, where the determination is subject to many kinds of error all known to tend in the same direction.

The coincidence of all these kinds of evidence does not, however, in the writer's belief, give absolute assurance that the values of the solar radiation may not be underestimated, a defect inherent in the method of observation at a single station.

We cannot go outside the atmosphere and prove that our determinations of its absorption are correct, but, at all events, the results are the best that can be reached at present from our single and low station. We may next consider their numerical values, and what they appear to show.

II. EXPERIMENTAL RESULTS.

1. *Atmospheric transmission.*—In the following table are given the atmospheric transmission coefficients for rays of certain wave-lengths for separate days of 1903–4, and the mean of numerous similar observations of 1901–2. It is to be remembered that these determinations are made only on the most cloudless days, so that they represent a transparency probably above the normal, though they do not include data of days when cumulus clouds were frequent, such as are often associated with a very deep blue intervening sky.

Attention has already been drawn by the writer[1] to the diminished transparency during the early months of 1903 as compared with 1901–2. The reader will now observe that this condition appears not to have continued so marked during the last three months of 1903, although the transparency did not recover fully its maximum value of 1901–2.

It seems probable that such long-continued alterations of

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[1] *Nature*, November 5, 1903.

TABLE I.

Atmospheric Transmission of Radiation for Zenith Sun.

DATE	PERCENTAGE TRANSMISSION FOR VERTICAL RAYS										
	$0^{\mu}.40$	$0^{\mu}.45$	$0^{\mu}.50$	$0^{\mu}.60$	$0^{\mu}.70$	$c^{\mu}.80$	$0^{\mu}.90$	$1^{\mu}.0$	$1^{\mu}.2$	$1^{\mu}.6$	$2^{\mu}.0$
1903, Feb. 19.......	67	64	66	72	76	80	83	85	86	90	92
26.......	48	60	66	68	74	83	88	90	93	93	92
Mar. 3.......	40	48	66	73	79	84	87	89	92	96	96
25.......	47	50	57	66	72	76	79	81	84	88	89
25.......	52	58	62	68	77	80	81	83	85	89	90
Apr. 17.......	55	60	69	77	80	82	87	90	94	97	97
28.......	39	52	56	64	71	74	76	78	82	88	89
29.......	46	49	56	66	72	76	77	80	83	88	90
July 7......	42	60	66	69	77	82	85	86	88	89	86
Aug. 24.......	39	52	60	59	78	84	86	87	89	90	89
Sept. 14.......	52	76	81	82	87	90	91	91	93	94	94
Oct. 14.......	64	70	76	80	85	88	89	91	91	(92)	(92)
29.......	52	59	65	75	80	82	84	85	88	91	(91)
Dec. 7.......	58	67	76	81	84	87	89	92	93	95	(94)
23.......	67	71	75	80	86	89	90	91	92	94	(94)
1904, Jan. 27.......	60	67	73	73	79	84	89	91	91	(91)	(91)
Feb. 11.......	42	55	58	59	70	78	84	89	92	95	(94)
Mean Results.											
1903, Feb.– .... Aug.	47.5	55.3	62.4	68.2	75.6	80.1	82.9	84.9	87.6	90.8	91.0
1903–4, Sept–........ Feb.	56.4	66.3	72.0	75.7	81.6	85.4	88.0	90.0	91.4	93.1	93.0
1903–4	51.2	59.8	65.2	70.1	78.1	82.3	85.0	87.0	89.2	91.8	91.6
1901–2	....	....	76.5	76.9	85.7	89.7	91.0	92.1	93.3	93.0	95.0

atmospheric transparency, if general over considerable areas of the Earth's surface, might directly influence observed temperatures, for if the air becomes more opaque, correspondingly less direct solar radiation remains in the beam to be absorbed at the Earth's surface, so that diminished surface temperatures naturally follow. It is of course quite possible that in so complicated a thing as climate other factors may tend to reduce such direct effects, but these are not immediately apparent.[1]

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[1] An effect of diminished atmospheric transparency upon plant growth seems equally probable; for it is generally conceded that certain functions of plant growth depend on a supply of violet radiations. It will be seen that the defect of atmospheric transparency noted in the early months of 1903 tended to reduce the intensity of the violet end of the spectrum most strongly. It would be of much interest to know if such a deficiency of violet rays may not have appreciably affected vegetation during this period.

As for the causes of the increased opacity of the atmosphere, nothing positive is certainly known, though some have surmised that the many and long-continued volcanic eruptions of 1902 may have distributed more fine dust than usual in the air. It can, on the other hand, be more definitely stated that the defect of transparency was not caused by increased water vapor; for the inferior transparency was observed on several of the dryest days on record, as shown by the form of the great water-vapor absorption bands in the infra-red spectrum.

2. *Solar radiation outside the atmosphere.*—The following table includes the best determinations of the solar radiation outside the atmosphere, made at the Smithsonian Observatory from October 1902, to March 1904. A part of these were included in Mr. Abbot's paper, above referred to, but as additional computations and data are given for several of the days, they are here repeated.[1] As was stated on an earlier page, the values are not regarded as absolute measures of the solar constant, but only as forming a series comparable among themselves, from which all known terrestrial variations are excluded, and which may furnish evidence of a suspected variability of the solar radiation.

Column 9, giving the radiation outside the atmosphere, is derived by multiplying the radiation at the Earth's surface, given in column 7, by the ratio of the area of the energy-curve outside the atmosphere to that at the Earth's surface, as given in columns 6 and 5, and correcting to mean solar distance by column 8. As already said, the agreement, both in columns 6 and 9, of the two computations of the same day furnishes two checks on the goodness of the day's work. Different instrumental conditions may, however, alter the values in column 6 as between different days.

It will be seen that the days of observation during 1903 fall in two groups, yielding high values and low values of solar radiation respectively, the former including all days prior to March 26, and the latter all days subsequent to that date. A possible return to the higher values is indicated by the observations of February 11, 1904, but we must await subsequent measures to confirm this.

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[1] The values of March 3, April 17, and April 28, included in Mr. Abbot's paper, are here omitted, because the observations of those days are of little weight.

TABLE II.

Measures of the "Solar Constant."

1	2	3	4	5	6	7	8	9
				Area of Energy Curve				
Date	Character of Observations	Hour Angle West	Air Mass	At Earth's Surface	Outside Atmosphere	Total Radiation at Earth's Surface (Calories per cm per Minute)	Correcting Factor for Solar Distance	Total Radiation Outside Atmosphere Corrected to Mean Solar Distance (Calories per cm per Minute)
1902, Oct. 9......	Fair	0^h 06^m	1.42			1.42	0.994	2.19
15......	Fair	1 31	1.62			1.44	0.989	2.19
22......	Fair	3 01	2.41			1.30	0.985	2.16
1903, Feb. 19......	Good	1 01	1.64	243	423	1.35	0.975	2.28
19......	Good	2 22	2.00	224	431	1.20	0.975	2.25
Mar. 25......	Excellent	2 01	1.45	186	355	1.19	0.996	2.26
25......	Excellent	3 52	2.50	137	365	0.83	0.996	2.21
26......	Excellent [1]	1 57	1.44	209	380	1.16	0.997	2.10
26......	Excellent	2 59	1.75	200	398	1.05	0.997	2.08
Apr. 29......	Excellent	1 39	1.18	219	377	1.11	1.018	1.94
29......	Excellent	2 26	1.31	202	370	1.05	1.018	1.97
July 7......	Fair	0 51	1.07	188	302	1.31	1.030	2.16
7......	Fair	3 36	1.51	162	303	1.10	1.030	2.11
Aug. 24......	Good	1 17	1.18	210	348	1.14	1.023	1.93
24......	Good	1 47	1.24	202	345	1.12	1.023	1.95
Oct. 14......	Good	1 58	1.72	250	408	1.23	0.990	1.98
14......	Good	2 25	1.88	246	408	1.18	0.990	1.94
29......	Good	0 59	1.69	233	415	1.13	0.981	1.97
Dec. 7......	Good	2 45	3.34	221	479	0.92	0.970	1.94
23......	Good	1 39	2.52	242	423	1.16	0.970	1.96
23......	Good	2 41	3.38	205	418	1.02	0.970	2.01
1904, Jan. 27......	Fair	1 49	2.20	205	369	1.18	0.970	2.05
27......	Fair	2 55	2.98	169	350	0.99	0.970	1.98
Feb. 11......	Fair	1 19	1.81	187	374	1.18	0.972	2.29
11......	Fair	2 29	2.27	168	381	1.02	0.972	2.24

III. POSSIBILITY OF CONSIDERABLE CHANGES IN THE AMOUNT OF SOLAR RADIATION OUTSIDE THE ATMOSPHERE.

Looking at the general results, these seem then to indicate a possibility that a rapid fall of solar radiation occurred about the close of March,[2] and that subsequently the radiation continued nearly or quite 10 per cent. less than before. This, if certain, would be important, and we may inquire what causes on the Sun could produce such a change, and what effects might be expected to be produced on the Earth if it occurred.

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[1] This day has been called "excellent," though in computations of the area of the energy-curve outside the atmosphere there is a larger difference than usual. But this is immediately explainable, if, as appears, the solar radiation itself was rapidly diminishing at the time; for this would result in too small apparent transmission coefficients, so that the second area computed would be larger than the first.

[2] It is of interest to note that a marked increase of Sun spots occurred on March 21. See Report of the Council, *Monthly Notices* of the Royal Astronomical Society, **64**, 357.

The writer showed nearly thirty years ago[1] that the envelope of the Sun profoundly influences by its absorption the radiation received by the Earth. While the absorption in the solar envelope is not exactly known, still so much is known that we may infer that if it were absent for a moment the Earth would receive nearly double its present amount of heat. If a variation of 10 per cent. in the transparency of this envelope occurred, nearly 10 per cent. of change in the solar radiation outside the Earth's atmosphere would follow.

If a fall of solar radiation did occur, there ought to have been a similar change of terrestrial temperatures afterward, and we may inquire how great this fall of temperature should be.

The Earth may be regarded as a body at a mean temperature of 290° absolute (17° C.), maintained at approximately constant temperature by a balance between solar radiation received and terrestrial radiation emitted. It is here assumed that all sources of heat other than the solar radiation are negligible, but if any or all of them are not so, the effect of their presence will be to reduce the effect on temperature of a fall in solar radiation.

Recent studies of German physicists have experimentally verified, for the perfect radiator, Stefan's law that the emission of a heated body is proportional to the fourth power of the temperature.[2] Other bodies not perfect radiators depart from this law in the sense that, while radiating less absolutely than the perfect radiator, their emission is more nearly proportional to a power of the temperature higher than the fourth.[3] Suppose T_1 to be the mean temperature of the Earth corresponding to a rate of solar radiation S_1, and T_2 that corresponding to S_2. Assume further that the reflecting power of the Earth remains unchanged, and that no appreciable heat is received from other sources than the Sun. Then

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[1] *Comptes Rendus*, **81**. 436, Sept. 6, 1875.

[2] O. LUMMER, *Rapports présentés au Congrès International de Physique*, **2**, 78-81, 1900.

[3] H. KAYSER, *Handbuch der Spectroscopie*, **2**, 77-82.

$$\left(\frac{T_2}{T_1}\right)^x = \frac{S_2}{S_1}, \text{ where } x > 4 .$$

Accordingly if, as supposed, S_2 is 9/10 S_1,

$$T_2 > 0.974\,T_1 .$$

If $T_1 = 290°$, then $T_2 > 282°.5$, and $T_1 - T_2 < 7°.5$ C.

It may then be stated that if the solar radiation remained for a long period of time at a value which would maintain the Earth's surface at a mean temperature of 17° C., and then fell 10 per cent., and so remained indefinitely, the fall of temperature of the Earth's surface would be less than 7°.5 C.

But if the solar radiation fluctuated between limits separated by 10 per cent., the fluctuation of terrestrial temperature would be less, according to the frequency of the fluctuations of solar radiation. Again, parts of the Earth's surface most closely associated with the oceans by the influences of winds, ocean currents, and rainfall would be least affected by such solar fluctuations, and would respond most slowly to a permanent alteration of solar radiation.

From the foregoing considerations we may then infer that the effect of a fall of 10 per cent. in the solar radiation should diminish the mean temperature of the Earth not more than 7°.5 C., and indefinitely less according to the shortness of the time elapsing before the radiation regained its former value. Stations near the sea, or subject to ocean currents and winds, or to heavy rainfall, would lag far behind stations in the interior of great continents in their temperature fluctuations.

When we come to the study of actual temperatures over the Earth's surface, we find that all collections of temperature data for single stations in the interior of great continents, covering long periods of time, exhibit nearly every year such considerable irregular variations from the normal temperatures that we are at no loss to find variations comparable in dimensions with those we are supposing to be caused by a fluctuating solar radiation. But it is only within the last year that we have the series of radiation measures with which to compare temperatures, and we now turn to recent temperatures as published in the *Internationaler Dekadenberichte* of the *Deutsche Seewarte* for nearly one hundred stations, for each ten-day period of 1903, and accompanied by normal temperatures representing the mean for the same ten-day periods of many former years.[1] From all the stations for which normal values are given, temperature departures have been computed here, and these departures have been averaged by geographical position in seven groups, comprising (1) North America, 20 stations; (2) Insular and Southwest Europe and North Africa, 18 stations; (3) Northwest Europe, 15 stations; (4) Central Europe, 10 stations; (5) European Russia, 11 stations; (6) Asiatic Russia, 8 stations; (7) High Altitudes in Europe, 7 stations. These seven groups of results are plotted in the accompanying chart (in which, to avoid confusion, the lines are alternately continuous and dotted), and as all seem to show the same tendency in more or less marked degree, no hesitation was felt in taking the general mean, giving observations of each station equal weight wherever present in the sum. The general mean for the 89 stations forms the (heavy) eighth line of the chart, and a comparison is invited between its course and that of the ninth and lowest line representing the observations of solar radiation made during 1903 at Washington.[2] In connection with this comparison the reader is reminded that during September an increasing transparency of the atmosphere was noted, which may have had the direct effect, discussed on a former page, of increasing terrestrial temperatures thereafter, and thus accounting for the observed rise of the mean temperature at the close of the year. If this be admitted, the general agreement of the observed temperatures with what radiation measures would lead us to expect, is certainly marked.

As for the total fall of temperature indicated by the charts,

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[1] The writer is indebted to Professor Cleveland Abbe and to Dr. W. F. R. Phillips, librarian of the U. S. Weather Bureau, for their aid in making accessible the publications of temperature data in possession of the Weather Bureau.

[2] It is to be regretted that only one day of observation, with at all satisfactory conditions, was secured between April 29 and August 24, and that (July 7) of less weight than the others.

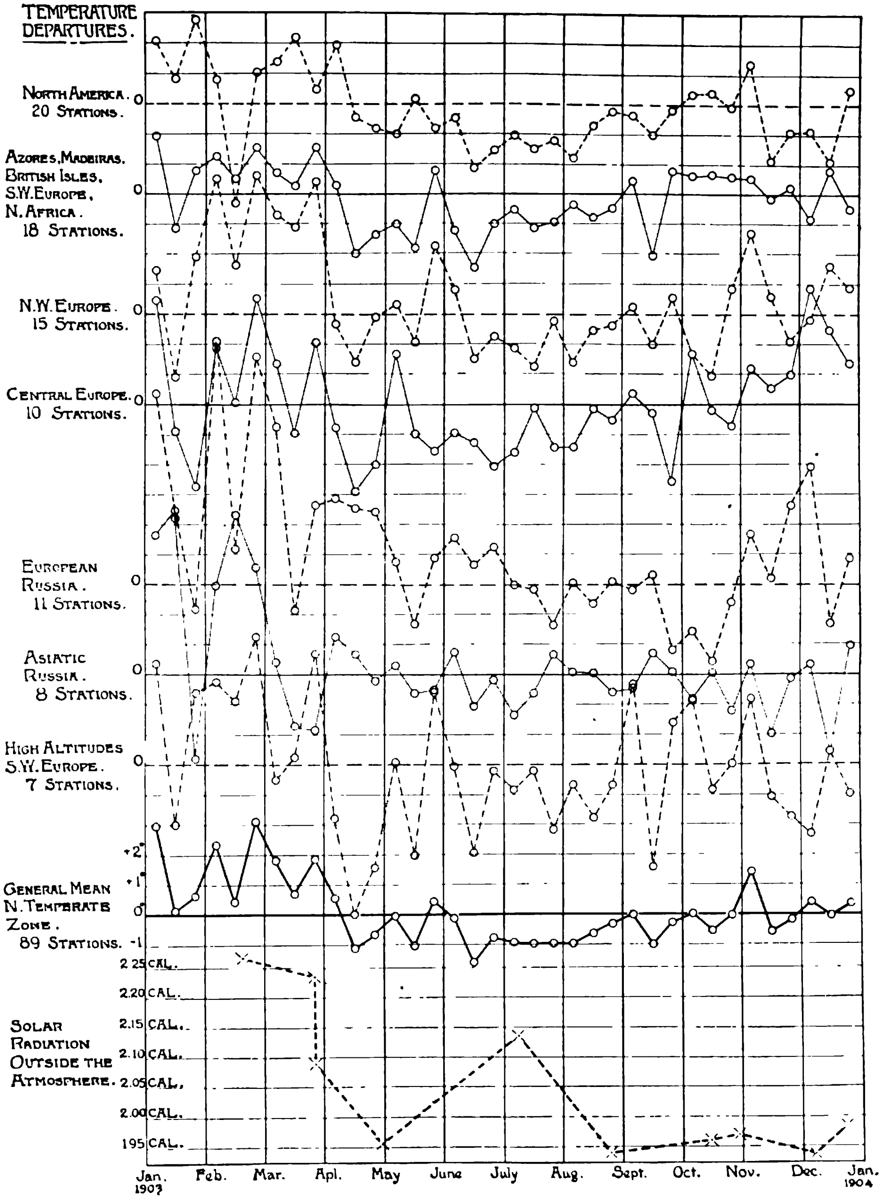
TEMPERATURE DEPARTURES.
North America. 20 Stations.
0
Azores, Madeiras, British Isles, S.W. Europe, N. Africa. 18 Stations.
0
N.W. Europe. 15 Stations.
0
Central Europe. 10 Stations.
0
European Russia. 11 Stations.
0
Asiatic Russia. 8 Stations.
0
High Altitudes S.W. Europe. 7 Stations.
0
General Mean N. Temperate Zone. 89 Stations.
+2°
+1°
0°
-1
2.25 CAL.
2.20 CAL.
2.15 CAL.
2.10 CAL.
2.05 CAL.
2.00 CAL.
1.95 CAL.
Solar Radiation Outside the Atmosphere.
Jan. 1903
Feb.
Mar.
Apl.
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.
Jan. 1904

FIG. 2.

that is seen to be a maximum for European and Asiatic Russia, the regions most removed from the influences of the oceans. The fall in the general mean for the land areas of the North Temperate zone[1] is, however, over 2° C., or about one-third of the maximum fall possible to be caused by a permanent diminution of solar radiation of 10 per cent. It is the absorption of heat by the oceans which retards the terrestrial change (if any) produced by change in the solar constant. Since the indirect effects of the absorption of solar radiation are felt in the oceans to depths of 2,000 meters, it may be shown that a change of 2° C. over the entire surface of the Earth would be delayed over a year.

SUMMARY AND CONCLUSION.

A series of determinations of the solar radiation outside the atmosphere (the solar constant)[2], extending from October 1902 to March 1904, has been made at the Smithsonian Astrophysical Observatory under the writer's direction.

Care has been exercised to determine all known sources of error which could seriously affect the values relatively to each other, and principally the varying absorption of the Earth's atmosphere. Though uncertainty must ever remain as to the absorption of this atmosphere, different kinds of evidence agree in supporting the accuracy of the estimates made of it and of the conclusions deduced from them.

The effects due to this absorption having been allowed for, the inference from these observations appears to be that the solar radiation itself fell off by about 10 per cent., beginning at the close of March 1903. I do not assert this without qualification, but if such a change in solar radiation did actually occur, a decrease of temperature on the Earth, which might be indefinitely less than $7^\circ.5$ C., ought to have followed it.

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[1] It would be of great interest to extend the discussion of temperature departures to include stations in the interior of South America, Africa, Australia, and southern Asia, but the data are not now available, and for many regions of these continents may long be wanting.

[2] I wish to renew my caution that the *absolute* values of the solar constant thus given are more likely to be found in defect than in excess.

On comparing the observed temperatures of 89 stations, distributed over the North Temperate Zone, with the mean temperatures of the same stations for many previous years, it is found that an average decrease of temperature of over 2° C. actually did follow the possible fall of the solar radiation, while the temperature continued low during the remainder of the year. Stations remote from the retarding influence of the oceans show a much greater variation than that of the general mean.

While it is difficult to conceive what influence, not solar, could have produced this rapid and *simultaneous* reduction of temperatures over the whole North Temperate Zone, and continued operative for so long a period, the evidence of solar variation cannot be said to be conclusive. Nevertheless, such a conclusion seems not an unreasonable inference from the data now at hand, and a continuation of these bolographic studies of solar radiation is of increasing interest, in view of their possible aid in forecasting terrestrial climatic changes, conceivably due to solar ones.

All the preceding observations, while under my general direction, have been conducted in detail by Mr. Abbot, to whom my thanks are especially due.

WASHINGTON, April 15, 1904.

A STUDY OF ENHANCED LINES OF TITANIUM, IRON, AND NICKEL.

By HERBERT M. REESE.

IN this investigation the enhanced lines in the spectra of titanium, iron and nickel were studied in the region from λ 4200 to λ 5000. In brief, the method consisted in photographing the arc spectrum and the spark spectrum of the same metal and noting those lines which were distinctly brighter in the spark than in the arc.

It is necessary to bear in mind, in discussing the subject of enhanced lines, that the arc and spark are perfectly independent sources, so that the relative duration of the two exposures determines whether every line in the spark shall be stronger than the line of identical wave-length in the arc, or just the reverse, or whether any intermediate condition shall exist. The only fixed data are the ratios of intensity of the arc lines among themselves and the corresponding ratios for the spark lines. Hence, if we fix the exposure times so that any line *A* has the same intensity in the photographs of arc and spark, any other line *B* may be regarded as enhanced if the ratio of its intensity to that of *A* is greater in the spark than in the arc, "depreciated" (if one may, in the emergency, apply such a meaning to this word) if this ratio is less in the spark than in the arc. Strictly speaking, the choice of the line *A* is arbitrary, but the classification of lines into those that are enhanced and those that are not enhanced acquires a physical significance when quite a number of the lines, say half the total number, or more, can at once be made of about equal intensity in the two spectra. This is generally the case, at least with spectra such as those of iron and titanium, which contain very many lines.

In order to facilitate the comparison, the camera of the ten-foot concave grating of the spectroscopic laboratory of the Yerkes Observatory was arranged so that several different exposures could be made upon the same plate. Several exposures of varying duration were made in the second-order spectrum with the spark as source of light; then, on the same or a different plate, several exposures of varying duration with the arc as source. After developing, etc., one spark exposure and one arc exposure were chosen such that the majority of the lines were of about the same intensity in the two. The plate was then carefully examined, and all lines were marked which were appreciably stronger or weaker in the spark than in the arc. The plate was then measured, in sections one-third of the total length, upon a Zeiss comparator. The measurements were made upon the spark spectrum; and, besides the lines previously marked, many other good lines were measured, partly to serve as standards for determining the wave-lengths of others, partly to be given as examples of the lines which are made of equal intensity in spark and arc. The plates were measured both with violet to left and with violet to right. In some cases eight settings in all were made upon a single line, in most cases only four. The wave-lengths were determined from the measurements in the usual way. Two lines of known wave-length (taken from Rowland's *Preliminary Table of Solar Spectrum Wave-Lengths*) were taken as standards, and the wave-lengths of the others determined by linear interpolation on the assumption that the spectrum was strictly normal. Then for such of these as were also given in Rowland's table, the residuals were plotted; and an error curve was drawn, by means of which all the wave-lengths obtained by interpolation were corrected. An idea of the degree of accuracy obtained may be gotten from a consideration of the final residuals in the case of those lines that are given in Rowland's table. The probable error determined from these lines in the cases of iron and titanium is ±0.008 tenth-meter for the determination of a single line. In the case of nickel the lines were less sharp and the continuous spectrum much stronger, so that the probable error is greater, viz., ±0.013 tenth-meter. In all cases, however, many lines were included which were difficult to measure, because of either extreme faintness or great breadth, so that the accuracy of measurement for good lines was greater than these figures would indicate.

In all cases the spectra showed some impurities, but so far as possible all lines not due to the element being studied were eliminated by a comparison with well-known tables of the wave-lengths of elements.

The current for generating the spark was supplied from a transformer wound in the ratio of 110 to 15,000. The current in the primary was about 19 amperes and the potential-difference about fifteen volts. In parallel with the secondary was a condenser of 0.0255 microfarads capacity. No self-induction was inserted in the spark circuit. The spark was passed between pieces of the metal under investigation about 3 mm apart. For iron and nickel cylindrical pieces of the metal were used, two or three millimeters in diameter; for titanium, pieces of irregular shape.

To obtain the arc spectrum, ordinary carbon poles were used, with pieces of the metal inserted in a hole in the lower carbon.

In the tables are given all lines which are regarded as enhanced or the reverse, all those which were used as standards for the determination of wave-lengths, and some others not included in either of the above categories, but inserted as examples of the lines regarded as unaffected in passing from arc to spark. Among the lines used as standards for wave-length are a number due to impurities.

The wave-length of the line as measured on my plates is given in the first column; the corresponding wave-length in the Sun, from Rowland's *Preliminary Table of Solar Spectrum Wave-Lengths*, is given in the second, if the line happens to be one of those used as standards for determining wave-lengths. The third and fourth columns give the intensities in spark and arc respectively. In the fifth are Lockyer's[1] wave-lengths of enhanced lines; while the sixth is devoted to general remarks.

A very strong line is designated by the intensity 10 or 9, while 1 denotes a very faint one. A line so faint as to be measured with great difficulty is denoted by the abbreviation "tr." or "trace." The letter "m." signifies that the line is missing.

[1] *Proc. R. S.*, 65, 452, 1899.

TITANIUM.

Pieces of the metal obtained from the electric furnace of Professor Moissan were used. It showed traces of vanadium, but no other impurities were detected with certainty.

Wave-Length	Rowland	Int. in Spark	Int. in Arc	Lockyer	Remarks
4224.87		3	3		
27.43		2–3	1–2	27.40	
38.00		4	4		
45.64		3	3		
48.39		2	tr. ?		Not identified.
49.27	49.27	3	3		
52.20		2	tr.		Not identified.
63.28	63.29	4	4		
71.91		2–1	tr.?		Not identified.
72.10		2	tr.		Not identified.
87.57	87.57	4	4		
88.04	88.04	3	2		
90.41	90.38	6	4	90.38	
93.39		2	1		Not identified.
93.68		2–1	tr.		Not identified.
94.28		6	4	94.20	
95.90	95.91	4	4		
4300.21	00.21	7	3	00.21	
02.10	02.08	5	3		
03.19		4	3		Not identified.
05.07		3	2		Not identified.
06.06	06.08	7	7		
08.05		6	4		
				08.60	
10.02		2–3	2		Not identified.
11.04		2–3	1–2		Not identified.
13.06	13.03	6	4	13.03	
14.93	14.96	4	4		
15.18		5	3	15.14	
16.95	16.96	3	2	16.96	
18.81		4	4		
21.12		4	2–3	21.20	
25.31	25.31	4	4		
30.41		4	2	30.50	
30.86	30.87	4	2–3	30.87	
35.01		3	3		
37.56		2–3	tr.		
38.06	38.08	6–7	5	38.08	
38.64		1–2	3		
41.52	41.53	4	3	41.53	
44.44	44.45	4	3	44.45	
51.00	51.00	4	2	51.00	
60.65	60.64	3	3		
64.78		2	m.		Not identified.
67.83	67.84	6	3	67.84	
70.86		2	m.		Not identified.
72.54		3	3		
74.99		4	2	74.90	

TITANIUM—*Continued.*

Wave-Length	Rowland	Int. in Spark	Int. in Arc	Lockyer	Remarks
4382.99		1	tr.		Not identified. [redacted]
83.71		2	1		Not identified. *Fe* 4383.72 ?
83.98		1	tr.		Not identified.
87.03	87.01	6	2	87.01	
91.19	91.19	3	2	91.19	
95.19	95.20	9	5	95.20	
96.00	96.01	3	2	96.01	
96.87		2–1	1		Not identified.
98.24		2–3	2		
98.45		2	1		
99.94	99.94	6	4	99.94	
4402.09		2	1		Not identified.
07.83	07.82	3	3		*V* Standard.
08.36		1–2	2		
08.67		2	3		
09.40		2–3	1		
09.68		2–3	1–2		
11.23	11.24	6	2	11.20	
12.09		2–3	1		
16.70		3	3		
17.90	17.88	5	3	17.88	
18.50	18.50	4	3		
22.10		3	1	21.93	
31.44		3	3		
32.27		2	tr.		
40.88		2	1		Not certainly identified as *Ti*.
41.89		3	2		
43.94	43.98	9	5	43.98	
44.72	44.73	3	2		
50.64	50.65	4	3	50.65	
56.81		2	m.		
64.62	64.62	4	3	64.62	
65.97	65.98	4	4		
68.66	68.66	9	5	68.66	
71.02	71.02	3	2		
80.75	80.75	3	3		
88.40		6	3	88.40	
95.17	95.18	3	3		
4501.45	01.45	9	5	01.45	
04.59		2–3	1–2		Not identified.
11.33		3	3		
22.08	22.07	5	5		
29.67		4	2	29.60	
34.15	34.14	7	4	34.14	
37.35		4	3		
41.18		3	2		
44.87	44.86	4	4		
46.66		4	2		Not iden. Weak *V* line at 46.57.
48.04	48.04	4	5		
49.83	49.81	9	5	49.81	
60.00	60.10	3	3		
63.94	63.94	7	5	63.94	
67.12		3	1		Not identified.

TITANIUM—*Continued.*

Wave-Length	Rowland	Int. in Spark	Int. in Arc	Lockyer	Remarks
4568.49		2–3	1		
69.00		4	2		Not identified.
72.17	72.16	9	5	72.16	
75.34		4	2		Not identified.
80.60	80.59	2	1		*V* Standard.
83.59		2	1		
90.14		5	3	90.13	
4609 55		4	3		
17.45	17.45	5	5		
29.52	29.52	4	4		
38.05	38.05	3	3		
50.20	50.19	4	4		
57.37	57.38	3	1		
87.98		2	1		
91.52	91.52	5	5		
93.85	93.85	2	2		
4708.85		2–3	1		Not identified.
10.38	10.37	5	5		
22.80	22.80	3	3		
23.35	23.36	3	3		
58.31	58.31	5	5		
62.97		1–2	1		Not identified.
64.08	64.11	4	2		
64.72		2–3	1–2		Not identified.
78.44	78.44	4	4		
80.16		5	3		Not identified.
96.40	96.37	3	3		
98.57		2	1		Not identified.
99.98	99.98	4	4		
4805.26		4	2		
12.42	12.43	2	2		
20.60	20.59	5	5		
36.31	36.31	2	2		
56.20		5	5		
65.82		2	1		Not identified.
68.44	68.45	5	5		
74.18		4	1		Not identified.
85.27	85.26	5	5		
92.58		3	m.		Not identified.
4900.10	00.10	5	5		
08.30		1	m.		Not identified.
11.39		5	1		
13.80	13.80	5	5		
17.62		2–3	tr.?		Not identified.
18.55		2–3	tr.?		Not identified.
23.68		2	1		Not identified.
28.52	28.51	4	4		
32.84		1	m.		Not identified.
33.04		1	m.		Not identified.
38.47		3	3		
63.41		2	1		Not identified.
75.52	75.53	3	3		
77.25		2–3	1		Not identified.

TITANIUM—*Continued.*

Wave-Length	Rowland	Int. in Spark	Int. in Arc	Lockyer	Remarks
4981.92	81.91	6	6		
82.72		3	1		Not identified.
84.58		4	1		Not identified.
89.34	89.33	4	4		
90.38		3	1		Not identified.
97.28	97.28	3	3		
98.33		4	1		Not identified.
5009.83	09.83	2	2		

It will be seen that this list includes all the enhanced lines given by Lockyer within this region, with the possible exception of the line at λ 4308.60, which is probably the same as my line at λ 4308.05, notwithstanding the great discrepancy in wave-length. It may be noted that Hasselberg gives an arc line at λ 4308.64, while Exner and Haschek give, for the spark, in addition to a weak line at λ 4308.67, a strong one at λ 4308.08. I carefully remeasured this line both in the spark and in the arc, and obtained the same value, λ 4308.05, in both cases. It is not likely that the iron line λ 4308.08 comes in here as an impurity, since the only other iron line suspected of being present is λ 4383.73, and this is much fainter.

Besides the lines noted by Lockyer, the table gives as enhanced the following lines, which have been identified as belonging to titanium, according to the tables of Hasselberg for the arc, or of Exner and Haschek for the spark:

4228.04
4305.07
37.56
98.24
98.45
4409.40
09.68
12.09
18.50
32.27
4440.88
41.89
44.72
56.81
71.02
4537.35
44.18
68.49
83.59
4609.55
4657.37
87.98
4764.08
4805.26
4911.39

The enhanced lines in the following list have not been identified in any other list of titanium lines, but may at least provisionally be ascribed to that metal:

4248.39
52.20
71.91
72.10
93.39
93.68
4303.19
05.07
10.02
4311.04
64.78
70.86
82.99
83.71
83.98
96.87
4402.99
40.88
4504.59
46.66
67.12
69.00
75.34
4708.85
62.97
64.72
80.16
4798.57
4865.82
74.18
92.58
4908.30
17.62
18.55
23.68
4932.84
33.04
63.41
77.25
82.72
84.58
90.38
98.33

The following lines, instead of being enhanced, are diminished in brightness on passing from the arc to the spark:

4338.64 4408.36 4408.67

IRON.

The only impurities detected were manganese and calcium. Many of the standard lines are omitted.

Wave-Length	Rowland	Int. in Spark	Int. in Arc	Lockyer	Remarks
4219.52	19.52	3-4	3		
20.50	20.51	1	tr.		
22.38	22.38	3	3		
25.63	25.62	2	2		
26.11	26.12	1	tr.		
26.58	26.58	1	tr.		
27.61	27.61	4	4		
29.69	29.68	tr.	m.		
30.54		tr.	m.		
30.86		tr.	m.		
33.17		1	m.		Not identified.
33.34	33.33	2	m.	33.25	
36.11	36.11	4	4		
38.99	38.97	2	2		
39.90	39.89	1	1		*Mn* standard.
40.53	40.54	1	m.		
42.89	42.90	tr.	m.		
46.24	46.25	1	m.		
47.98		1	tr.		Not identified.
50.29	50.29	5	5		
50.96	50.94	6	5		
53.73		tr.	m.		Not identified.
53.90		1	m.		
54.50	54.50	tr.	1		
60.65	60.64	6	6		
63.60		1	tr.		Not identified.
67.11	67.12	1	1		
68.36		1	tr.		Not identified.
68.94	68.92	3	tr.		
71.33	71.32	5	5		

IRON—*Continued.*

Wave-Length	Rowland	Int. in Spark	Int. in Arc	Lockyer	Remarks
4271.94	71.93	7	6		
74.90		2	1		
77.88		1	m.		
79.60	79.59	tr.	m.		
82.56	82.56	4	4		
85.59	85.60	1-2	1		
87.69		1	m.		Not identified.
88.32		tr.	m.		
90.50	90.54	tr.	m.		
94.29	94.30	5	5		
96.08		tr.	m.		
96.74		tr.	m.	96.65	
97.26		1	m.		Not identified.
98.21	98.20	2	1		
99.41	99.41	5	5		
4303.34		1	m.		
05.08		2-3	m.		Not identified.
07.53		1	m.		
08.08	08.08	8	7		
09.20	09.20	1	tr.		
09.55	09.54	2	2		
10.28		tr.	m.		
11.07		2-3	tr.		
15.25	15.26	3	3		
22.92		3	tr.		
25.95	25.94	8	7		
28.95		2	tr.		
31.96		1	m.		
36.92		tr.	m.		Not identified.
37.22	37.22	3	3		
43.45	43.43	tr.	m.		
43.89	43.86	tr.	m.		
46.73	46.72	tr.	m.		
51.94	51.95	2	m.	51.93	
52.91	52.91	3	3		
67.75	67.75	2	1-2		
71.52		1	tr.		
73.75	73.73	tr.	m.		
76.10	76.11	3	3		
80.67		3	tr.		
83.73	83.72	10	9		
85.55		1	m.	85.55	
86.77		3	tr.		
88.06	88.06	1	tr.		
88.58	88.57	1-2	1		
89.81		tr.	m.		Not identified.
90.05		tr.	m.		
91.12	91.12	1	tr.		
92.68		tr.	m.		
92.84		tr.	m.		Not identified.
4401.46	01.46	1	tr.		
01.86		2	tr.		Not identified.

IRON—*Continued.*

Wave-Length	Rowland	Int. in Spark	Int. in Arc	Lockyer	Remarks
4404.93	04.93	9	7-8		
07.99		2-3	m.		
08.59	08.58	2	2		
12.22		2	tr.		
15.32	15.29	7	6-7		
18.36		2	m.		
21.69		1	m.		Not identified.
21.99		tr.	m.		Not identified.
22.74	22.74	2	2		
23.98	24.01	1	m.		
27.48	27.48	3	3		
33.38	33.39	2	1		
42.51	42.51	3	3		
47.89	47.89	3	3		
50.51	50.48	1	m.		
59.30	59.30	3	3		
61.82	61.82	2	2		
66.72	66.73	4	3-4		
69.56	69.54	2	2		
76.19	76.18	3	3		
77.43		1	m.		
89.38		tr.	m.	89.35	Not identified.
89.90	89.91	1	1		
91.58		1	m.	91.57	
94.74	94.74	3	3		
4504.17		tr.	m.		Not identified.
08.46	08.46	1-2	m.	08.46	
15.51		1	m.	15.51	
20.39	20.40	1	m.	20.40	
22.81		2	m.	22.69	
25.66		tr.	m.		Not identified.
28.80	28.80	4	4		
31.32	31.33	2	2		
31.88		1	m.		Not identified, hazy.
48.02	48.02	1-2	1		
49.66	49.64	2-3	m.	49.64	
56.07		1	m.	56.10	
56.30	56.31	1	1		
76.51		tr.	m.	76.51	Not identified.
84.02	84.02	3	m.	84.02	
98.30	98.30	tr.	m.		
4603.12	03.13	2	2		
19.46	19.47	1	tr.		
29.50		1	m.	29.60	
37.69	37.68	1	tr.		
38.21	38.19	1	tr.		
47.62	47.62	2	2		
69.34	69.35	tr.	m.		
73.36	73.35	tr.	m.		
91.59	91.60	1	tr.		
4710.46	10.47	1	tr.		
54.23	54.23	1	2		*Mn* standard.

IRON—*Continued.*

Wave-Length	Rowland	Int. in Spark	Int. in Arc	Lockyer	Remarks
4783.62	83.61	1	2		*Mn* standard.
86.99		1	tr.?		
89.83	89.85	1–2	tr.		
4823.69		1	2		
71.50	71.51	3	3		
90.94	90.95	3	3		
91.68	91.68	4	4		
4924.11	24.11	3	m.	24.11	
97.99		tr.	m.		Not identified.
5002.05		2	1		
05.90	05.90	2	tr.		
06.31	06.31	2	1–2		

Lockyer gives five enhanced lines in this region of the iron spectrum which are not included in the above table. These are λλ4302.35, 4451.75, 4462.30, 4541.40, and 4635.40. For the first line Lockyer gives the intensities 2–3 in the spark and 2 in the arc. On my plates it appears a trifle stronger in the spark than in the arc, but so little that I hardly felt justified in classifying it with the enhanced lines. The line 4451.75 is not enhanced on my plates, nor is the line 4462.18, which is probably the same as Lockyer's λ4462.30. My plates do not show λ4541.40 nor λ4635.40.

The table gives the following enhanced lines not given by Lockyer, but all identified as iron lines:

4219.52
20.50
26.11
26.58
29.69
30.54
30.86
40.53
42.89
46.24
50.96
53.90
68.94
71.94
4274.90
77.88
79.60
85.59
88.32
90.50
96.08
98.21
4303.34
07.53
08.08
09.20
10.28
11.07
4322.92
25.95
28.95
31.96
43.45
43.89
46.73
67.75
71.52
73.75
80.67
83.73
86.77
88.06
4388.58
90.05
91.12
92.68
4401.46
04.93
07.99
12.22
15.32
18.36
23.98
33.38
50.51
66.72
4477.43
4548.02
98.30
4619.46
37.69
38.21
69.34
73.36
91.59
4786.99
89.83
5002.05
05.90
06.31

Many of these are mere traces and are added only for the sake of completeness.

The following lines are also enhanced, but have not been identified in any lists of iron lines:

4233.17
47.98
53.73
63.60
4268.36
87.69
97.26
4303.34
4336.92
89.81
92.84
4401.86
4421.69
21.99
4504.17
25.66
4531.88
76.51
4997.99

The only line stronger in the arc than in the spark is λ4823.69.

NICKEL.

The metal used proved to contain traces of iron, manganese, and cobalt, but no other impurities were detected. Lockyer did not investigate this metal.

Wave-Length	Rowland	Int. in Spark	Int. in Arc	Remarks
4231.22	31.18	2-3	2	
32.14		tr.	m.	Not identified.
35.45	35.45	2	m.	*Mn* standard.
36.12	36.11	1	1	*Fe* standard.
44.94	44.96	2	m.	
50.28	50.29	1	1	*Fe* standard.
58.97		2-3	m.	Not identified.
60.63	60.64	2	2	*Fe* standard.
63.36		1-2	m.	Not identified.
71.33	71.32	1	1	*Fe* standard.
71.91	71.93	2	2	*Fe* standard.
79.36		4	m.	
84.85	84.84	3	3	
88.18	88.15	4	4	
91.19		tr.	m.	Not identified.
94.28	94.30	1	1	*Fe* standard.
97.15		1	m.	
98.70	98.68	1-2	1	
4307.45		1-2	1	
08.07	08.08	2	2	*Fe* standard.
25.93	25.94	2	2	
30.92	30.87	1	1	
31.81	31.81	3	3	
56.10	56.16	2	2	
59.76	59.65	3	3	
62.28		4	m.	
68.49	68.46	2	1-2	
70.22	70.19	1	1	
70.57		1-2	m.	Not identified.

NICKEL—*Continued.*

Wave-Length	Rowland	Int. in Spark	Int. in Arc	Remarks
4383.71	83.72	3	4	*Fe* standard.
98.66		2	1-2	
99.80	99.78	1-2	1-2	
4401.09	01.02	2	2	
01.73	01.71	6	6	
04.92	04.93	2	2-3	*Fe* standard.
10.66	10.68	1-2	2	
15.06	15.05	4	m.	*Mn* standard.
15.28	15.29	2	2	*Fe* standard.
23.20		1-2	1	
24.00	24.01	1	m.	*Fe* standard.
37.15	37.11	2	2	
51.74	51.75	1-2	m.	*Mn* standard.
59.21	59.20	6	6	
62.62	62.62	3	3	
63.58	63.57	1	1	
66.60	66.55	2	2	
70.64	70.65	4	4	
72.64		1	m.	Not identified.
80.76	80.75	1	1	
90.70	90.70	1	1	
4503.96		1	m.	Not identified.
05.62		1	m.	Not identified.
09.42		3	m.	
13.17	13.16	2	2	
20.15	20.16	1	1	
24.92		3	m.	Not identified.
31.13	31.12	1-2	1	*Co* standard.
32.48		tr.	m.	Not identified.
47.11	47.10	3	3	
47.40	47.40	2	2	
51.41	51.40	2	2	
53.32	53.35	1	2	
60.10	60.10	1	1	
76.48		tr.	m.	Not identified.
80.79	80.76	1	1	
85.85		2-3	m.	Not identified.
92.71	92.71	4	4	
4600.54	00.54	3	3	
05.18	05.17	4	4	
06.39	06.40	2	2-3	
08.38		1	tr.	Not identified.
48.84	48.84	5	6	
65.72		3	m.	Not identified.
67.17	67.16	2	2	
67.94	67.94	2	2	
79.31		4	m.	Not identified.
86.40	86.40	4	4	
4701.73	01.71	3	3	
03.06	03.09	3	3	
12.25	12.26	1	1	
14.61	14.60	6	6	

NICKEL—*Continued.*

Wave-Length	Rowland	Int. in Spark	Int. in Arc	Remarks
4715.93	15.95	3	3	
32.65	32.64	2	2	
52.26	52.29	1	1	
52.58	52.61	2	2	
54.22	54.22	1	m.	*Mn* standard.
54.96	54.95	2	2	
56.71	56.70	4	4	
62.54	62.57	1	m.	*Mn* standard.
62.80	62.82	2	2–3	
64.13	64.11	3	3	
66.63	66.62	tr.	m.	*Mn* standard.
86.45	86.47	1	1	
86.73	86.73	4	4	
4807.18	07.19	3	3	
12.17	12.18	1	1	
18.05	18 00	1	1	
23.71	23.70	1	tr.	*Mn* standard.
29.22	29.21	3–4	4	
31.38	31.36	3	3	
38.86	38.84	2	2	
52.75		1	2	
55.59	55.60	4	4	
57.58	57.58	2	2	
66.46	66.46	4	4	
71.01	71.00	1–2	2	
73.63	73.63	3	3	
75.00	74.98	1	1	
75.99		1	m.	Not identified.
87.18	87.19	1	1	
4904.58		4	4–5	
12.21	12.20	1–2	2	
14.14		1–2	2	
18.55	18.54	3	3	
18.89	18.89	1	1	
25.74	25.75	1–2	1–2	
36.01	36.02	2	2	
37.48	37.52	1	2	
53.40	53.39	1–2	1–2	
71.50	71.53	1	1–2	
73.68		1–2	1	Not identified.
80.33	80.35	3–4	4	
80.55		1	1	
83.64		1	1	
84.29	84.30	3–4	3–4	
98.42	98.41	1	1–2	
5000.50	00.53	1–2	2	
12.64	12.62	1–2	1–2	

The enhanced lines in the above table certainly belonging to nickel are:

4231.22	4279.36	4298.70	4362.28	4398.66
44.94	97.15	4307.45	68.49	4509.42

The following have not been identified:

4232.14
58.97
63.36
91.19
4370.57
4472.64
4503.96
05.62
4524.92
32.48
76.48
4585.85
4608.38
65.72
4679.31
4775.99
4973.68

The following lines are stronger in the arc than in the spark:

4410.66
4553.32
4609.39
4684.84
4762.82
4829.22
4871.01
4904.58
12.21
4914.14
71.50
80.33
4998.42
5000.50

It is interesting to note that most of these lie in the same part of the spectrum. In no case is the difference in intensity between arc and spark at all great, and we may interpret the facts by saying that for the less refrangible part of the region investitigated a better matching of the intensities of the lines would have been obtained by exposing to the spark spectrum a little longer.

A comparison of the above tables with Rowland's table shows a number of lines which seem to have the same wave-length, well within the limits of error, as lines in the solar spectrum which have not been ascribed by him to any element. Omitting all lines with intensity less than 0 in the Sun, the most striking cases are the following.

λ Spark	Int. in Spark	λ (Rowland)	Int. in ⊙	Element	λ Spark	Int. in Spark	λ (Rowland)	Int. in ⊙	Element
4253.00	1	53.888	0	*Fe*	4515.51	1	15.508	3	*Fe*
4303.34	1	03.337	2	*Fe*	22.81	2	22.802	3	*Fe*
10.02	2-3	09.993	0	*Ti*	29.67	4	29.656	1	*Ti*
21.12	4	21.119	2	*Ti*	44.18	3	44.190	1	*Ti*
30.41	4	30.405	1	*Ti*	68.49	2-3	68.499	0	*Ti*
62.28	4	62.262	0	*Ni*	83.59	2	83.587	0	*Ti*
80.67	3	80.655	0	*Fe*	90.14	5	90.126	3	*Ti*
85.55	1	85.548	2	*Fe*	4708.85	2-3	08.846	2	*Ti*
98.45	3	98.400	0	*Ti*	62.97	1-2	62.969	0	*Ti*
4409.40	2-3	09.408	0	*Ti*	64.72	2-3	64.720	0	*Ti*
09.68	2-3	09.683	1	*Ti*	4852.75	1	52.743	2	*Ni*
12.09	2-3	12.092	1	*Ti*	74.18	4	74.196	0	*Ti*
22.10	3	22.104	1	*Ti*	4904.58	4	04.597	3	*Ni*
88.40	6	88.403	1	*Ti*	11.39	5	11.374	1	*Ti*
91.58	1	91.570	2	*Fe*	14.14	1-2	14.150	2	*Ni*

It is not claimed that these are all cases of actual coincidence, though probably most of them are. Before being finally accepted they should be carefully examined for coincidence by photographing the arc and the solar spectrum in juxtaposition,

This research was undertaken at the suggestion of Mr. E. B. Frost, to whom many thanks are due for interest shown in the work.

YERKES OBSERVATORY,
April 28, 1904.

THE RADIAL VELOCITIES OF THE BRIGHTER STARS IN THE *PLEIADES*.

By WALTER S. ADAMS.

THE only attempt which has hitherto been made to determine either the relative or absolute radial velocities of the stars in the *Pleiades* group is that of Pickering,[1] who used an objective prism, and found that the relative motion of the seven brightest stars is probably less than 30 km a second. The great difficulty in the way of such a determination, and the one which has led to the neglect of these important stars in modern radial velocity work, is the character of their spectra. These are of the advanced helium type, as Miss Clerke well designates them, and it is in this type that the greatest difficulty is found in securing lines upon which accurate measurements can be made; the helium lines having lost the strength and relatively well defined character which they possess in the representative helium stars, while the type is not sufficiently advanced to show, to any measurable extent at least, the metallic lines which are characteristic of the Sirian stars.

It is clear that in dealing with spectra of this nature the best results are to be expected from the use of comparatively low dispersion. The loss of scale in the plates is more than counterbalanced by the superior definition and increase in apparent strength of the lines present, and the gain in the extent of measurable spectrum is of very great importance in the case of spectra in which the lines are so extremely limited in number. An interesting comparison of results in a case of this nature is given by Hartmann[2] for δ *Orionis*, and his conclusions may be applied with still more emphasis to the stars in the *Pleiades*, since the lines present are considerably weaker and more diffuse than in δ *Orionis*. An exception should be made here in the case of *Maia* (20 *Tauri*), the spectrum of which can be studied to advantage with high dispersion. Reference will be made later to the characteristic features of its spectrum.

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[1] ASTROPHYSICAL JOURNAL, **4**, 372–3, 1806.

[2] *Sitzungsberichte der Kgl. Akad. der Wissenschaften zu* ***Berlin***, **14**, 14, 1904.

All of the plates used in this investigation, with two exceptions, were obtained with the Bruce spectrograph modified for use with one prism, a form in which it has been employed for a large part of the radial velocity work during the past year. The remaining two plates, both of *Maia*, were obtained with the regular three-prism train. The scale of the low-dispersion plates for the position of minimum deviation at $\lambda 4480$ is $1 \text{ mm} \doteq 30$ tenth-meters, and the extent of spectrum within which measures have been made is from the helium line at $\lambda 4026$ to $H\beta$ at $\lambda 4862$.

Six stars are included in this discussion, for all of which at least three plates have been obtained. It was originally intended to include *Pleione* and *Celaeno* as well, but unfortunately the lack of suitable observing weather has made this impossible. The remarkable character of the spectrum of *Pleione* would make the investigation of this star of particular interest.

In view of the extreme difficulty of the measures involved, it has seemed best to repeat so far as possible, and accordingly duplicate measurements have been made throughout. Every effort has been used to keep these entirely independent: the second measurement has always been at a considerable interval after the first so that there might be no tendency on the part of the observer unconsciously to carry in his mind any recollection of the estimated positions of the lines involved. This is a matter of considerable importance in the case of such spectra as those of the *Pleiades*, since the excessively broad and ill-defined character of the lines occasionally gives rise to an option in the estimated position of a line, and complete independence of judgment in such a case is essential to guard against systematic error.

The wide range in the quality of the lines measured has made some process of weighting necessary, and accordingly the procedure has been adopted of assigning a weight to each line at the time of measurement, and combining these weights to form the result given by the plate.[1] In the case of two measurements of the same plate, however, the simple mean of the two results has been taken as the final value. The difference in the number of lines measured in such cases is usually small, and the additional lines included are invariably of low weight, and would affect the result but slightly.

The table which follows gives the results for five of the stars. In addition to the name of each star, Bessel's number is added for convenience in reference. The magnitudes given are those of the *Harvard Photometry*. The velocities are, of course, in all cases referred to the Sun.

Electra (17 *Tauri*); Mag. 3.8.

Plate	Date	FIRST MEASURE		SECOND MEASURE		Mean Velocity
		Velocity	No. of lines	Velocity	No. of lines	
		km		km		km
I B 110	1903, October 10	+ 16.2	4	+ 17.5	4	+ 16.8
165	October 30	11.0	5	15.4	5	13.2
271	1904, January 29	12.7	4	14.4	3	13.5

Mean + 15

Taygeta (19 *Tauri*); Mag. 4.4

I B 257	1904, January 23	+ 4.5	5	+ 4.1	4	+ 4.3
295	March 19	3.9	6	1.5	6	2.7
303	April 15	2.6	5	1.8	4	2.2

Mean + 3

Merope (23 *Tauri*); Mag. 4.2

I B 234	1903, December 27	+ 6.0	4	+ 6.7	5	+ 6.4
293	1904, March 19	3.9	5	6.0	6	5.0
313	April 16	8.4	4	6.7	4	7.5

Mean + 6

Alcyone (25 *Tauri*); Mag. 3.0

I B 164	1903, October 30	+ 16.4	3	+ 18.3	4	+ 17.3
216	December 4	12.3	5	15.5	3	13.9
221	December 25	14.8	4	11.8	5	13.3

Mean + 15

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[1] See FROST and ADAMS, "Radial Velocity of Twenty Stars Having Spectra of the *Orion* Type." *Publications of the Yerkes Observatory*, 2, 151, 1903.

Atlas (27 *Tauri*); Mag. 3.8

I B 163	1903, October 30	+ 15.6	4	+ 12.4	5	+ 14.0
220	December 25	11.5	3	13.3	5	12.4
272	1904, January 29	14.7	4	14.5	3	14.6
282	February 26	9.5	6	9.9	4	9.7

Mean + 13

So far as any estimate can be formed of the degree of accuracy of the above determinations, it is probable that those for *Taygeta* are most accurate, and those for *Merope* least so, with little to choose among the other three stars. The conclusion in regard to *Taygeta* is due to the fact that its spectrum differs sensibly from that of the other stars in the list, the lines being stronger and narrower as well as slightly better defined. None of the plates of *Alcyone* show evidence of the presence of a bright line at $H\beta$.

The observations of *Maia* lead to the interesting conclusion that the velocity of this star is variable. Seven plates have been obtained, as indicated in the list which follows. B 545 and B 552 were taken with a dispersion of three prisms.

Maia (20 *Tauri*); Mag. 4.0.

Plate	Date	First Measure		Second Measure		Mean Velocity
		Velocity	No. of lines	Velocity	No. of lines	
		km		km		km
I B 166	1903, October 30	− 7.0	5	− 7.8	4	− 7.4
219	December 25	+ 21.0	2	+ 20.8	5	+ 20.9
235	December 27	− 6.5	4	− 4.0	5	− 5.2
244	1904, January 2	+ 0.8	7	+ 7.8	4	+ 4.3
B 545	January 9	+ 1.7	6	+ 2.3	7	+ 2.0
I B 294	March 19	+ 10.0	9	+ 7.8	8	+ 8.9
B 552	March 25	+ 2.0	6	+ 1.5	4	+ 1.8

Though the range here indicated is not very large, the character of the spectrum fortunately is such as to make it almost certainly real. The lines without exception are greatly superior to those in the spectra of any of the other stars in the list for purposes of measurement, the hydrogen lines being strong and narrow, and the magnesium line at λ 4481 well defined. The spectrum is, in fact, decidedly at variance with what we should expect for a star closely involved in nebulosity, and is in marked contrast to that of the similarly situated star ***Merope.*** This fact, considered in connection with the low absolute velocity which an inspection of the measures indicates with reasonable certainty for the system of *Maia* (assuming its binary character to be proven), may perhaps warrant the suspicion that this star as well as its neighbor *Taygeta*, is not physically connected with the nebulosity. On the other hand, the character of the spectrum of the remaining four stars is precisely of the sort which is encountered among nebulous stars, and would furnish a strong presumption in favor of their connection with the nebulosity in this case. As is well known, the proper motions of all the brighter stars in the *Pleiades* are small. Newcomb[1] finds for *Alcyone* the annual proper motion

$$\Delta\alpha = +0''.0132\,;\ \Delta\delta = -0''.0587;\ \text{in a great circle } 0''.060;$$

and this motion is found to satisfy the remaining stars within the limits of error of the observations. A similar conclusion is reached by Elkin[2] as to the absence of relative motion among the bright stars of the group. The small value of the radial velocity of *Merope* would seem to argue against its association with *Alcyone*, *Atlas*, and *Electra*, but, in view of the low degree of accuracy attained in its determination, the argument is by no means strong.

The following brief summary of the results for the stars which we have considered here may be of convenience:

Electra	+14 km
Taygeta	+ 3
Maia	Variable
Merope	+ 6
Alcyone	+15
Atlas	+13

In conclusion, emphasis should once more be laid upon the character of measures on spectra of this nature. It is certainly not too much to say that ranges of at least 5 km between successive plates of the same star, or between duplicate measurements of the same plate, may well be expected in the case of any one of the stars in the above list, except perhaps *Maia* and *Taygeta*. Accordingly, care should be taken not to draw conclusions from accordances which may easily be illusory.

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[1] *Standard Clock and Zodiacal Stars.*

[2] "Relative Positions of the Principal Stars in the Group of the ***Pleiades.***" *Transactions of the Astronomical Observatory of Yale University*, I, Part I, 1887.

I am indebted to Mr. F. R. Sullivan for efficient assistance in guiding during most of the exposures on the stars here discussed.

YERKES OBSERVATORY,
April 25, 1904.

VARIABLE STARS IN NEBULA OF *ORION* IN CONNECTION WITH CHART FOR *T ORIONIS.*

By JOHN G. HAGEN, S. J.

THE variable stars in the Great Nebula of *Orion*, or in the star cluster of this nebula, seem to belong to that peculiar type which has been recognized during the past ten years as the "cluster type." They are generally too faint for telescopes of less than fifteen inches aperture, and are outside the limit of visibility adopted for the *Atlas of Variable Stars.*

The few observers who can reach these *Orion* variables with their instruments will probably find Bond's chart (Vol. V, *Annals of Harvard College Observatory*) a sufficient guide for identification, especially since Hartwig (*A. N.*, **164**, 415, 1904) and Pickering (*Harvard Circular* No. 78) have given Bond's numbers corresponding to many of these variables. The recent publication of six small charts by Wolf (*A. N.*, **164**, 393, 1894) for finding those of his *Orion* variables which are within or near the Great Nebula, suggested the idea of making the chart for *T Orionis* of the *Atlas Stellarum Variabilium* available for the same purpose. It is No. 1986 of Series I.

1. Four of Wolf's circular charts (III–VI) fall on the sheet of *T Orionis*, two of them entirely inside the graduation net. His Chart I contains only one confirmed variable (a_1), and Chart II none, the only variable (b_0) being among the suspected variables (No. 3) of Professor Pickering's Circular.[1] Thus out of the 14 variables on Wolf's charts, 12 fall on the sheet of *T Orionis*, one-half of them within the net.

Professor Pickering's *Circular* No. 78 contains 71 well-confirmed variable stars and 35 suspected ones. Of these variables, 57 (not identical with any of Wolf's) can be conveniently plotted on the sheet for *T Orionis*, viz., 40 well-confirmed and 17 suspected variables. Some other stars of the circular which would fall on the printed title of the sheet are not counted.

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[1] Another chart, recently published by Wolf (*A. N.* **165**, 30, 1894), contains one variable, about four degrees north of *T Orionis*.

Adding to these 69 variables *T Orionis*, and another star found to vary by the writer, and two more stars suspected of variability by Pogson and Schmidt, we shall have 73 variable stars, more or less confirmed, on the single Atlas chart prepared for *T Orionis*.

2. In order to facilitate the identification of these objects, a list of 104 stars has been prepared. Among these are 25 which were merely copied from the catalogue of the Atlas, and are printed on the chart. They fall within Wolf's Charts IV and VI (except two), and can readily be identified on them. Five of these 25 stars are variables (confirmed or suspected), one of them being *T* and the others Nos. 66, 35, 60, 19 of the Atlas catalogue. The remaining 79 stars of the list will have to be plotted on the sheet for *T Orionis*. Eleven of them represent the *B. D.* stars within Wolf's Charts III and V, but without the net of the Atlas. The other 68 stars are variables (in the sense before mentioned), and, together with the five copied from the Atlas catalogue, make up the number 73 of the preceding paragraph.

After these 79 stars are plotted, it will be found convenient to have the four circles drawn which represent Wolf's Charts III–VI. The fainter stars of these charts (the co-ordinates of which were not given) may then be inserted from eye estimates. The common radius of these circles is 10′.5, which is to be measured from the net of the chart for *T Orionis;* and their centers relative to the middle of the chart (including I and II, which fall outside the sheet) have the co-ordinates:

Chart I	$\Delta\alpha = +5^m\ 40^s$,	$\Delta\delta = +81'.1$
II	$-3\ \ 42$	$+25.4$
III	$-1\ \ 26$	$+46.1$
IV	$-0\ \ 49$	-10.0
V	$-0\ \ 12$	$+37.0$
VI	$+0\ \ 25$	$+13.1$

3. The subjoined list of 104 stars is constructed as follows: The first column gives the numbers in Professor Pickering's *Circular* 78, those in parenthesis referring to his Table II of suspected variables. The next two columns contain exclusively Wolf's designation in his article in *Astronomische Nachrichten*, No. 3935, to make his variables and reference stars recognizable

at a glance. The column headed "Chart" designates Wolf's Charts III–VI on which the stars fall. The heading "*A. S. V.*" denotes the numbers of the Atlas for the 25 stars copied from its catalogue. In the column "Mag." the letter *v* marks the certain variables, while the interrogation point (?) refers to the unconfirmed variables. The magnitudes are those of the Atlas, except for stars outside the net, for which the *B. D.* magnitudes are given. The Δα and Δδ denote the co-ordinates of the stars relative to the center of the chart. They were computed from the lists of Wolf and Pickering, and hold for 1900.

P	Wolf		Chart	*A.S.V.*	Mag.	Δα	Δδ
2					*v*	$-2^m\ 29^s$	+ 6'.3
3	36.1903	d_1			*v*	19	+16.3
4					*v*	19	+44.8
5					*v*	19	+44.2
6					*v*	16	+26.7
(6)					?	5	− 2.9
(7)	81.1901	08	III		?	2 2	+49.6
9					*v*	1 57	−13.4
10	37.1903	d_0	III		*v*	56	+40.4
12					*v*	47	− 8.7
13					*v*	44	+14.6
14			III		*v*	41	+38.3
(8)					?	41	− 3.9
15					*v*	35	+23.8
	−4°1167	*1	III		7.5	29	+39.5
17					*v*	27	− 2.6
(9)					?	27	+31.3
			III		9.5	25	+54.6
18			III		*v*	25	+42.9
			IV	43	10.1	17	−17.4
	−5°1301	*1	IV	23	9.2	16	−14.4
			IV	20	9.1	15	−12.9
19					*v*	13	−37.2
20			IV		*v*	13	− 6.6
21					*v*	10	+ 5.6
22			IV		*v*	9	−17.7
23					*v*	7	+17.6
	−5°1305	*2	IV	11	8.4	3	− 5.7
24					*v*	1	−29.6
25	39.1903	k_0	III		*v*	1 1	+48.2
			IV	41	9.8	0 59	− 4.8
(10)					?	59	+24.9
			III		9.3	57	+43.0
			IV	18	9.0	54	− 2.1
26	40.1903	d_2	IV		*v*	54	−18.3
27			IV		*v*	54	−13.3
29					*v*	52	−26.2
30			V		*v*	−0 51	+37.6

P	Wolf		Chart	*A.S.V.*	Mag.	$\Delta\alpha$	$\Delta\delta$
(12)					?	$-0^m\ 51^s$	+5'.4
(13)			IV		?	50	−16.1
					?	48	−32.2 (1)
	−4°1179	*2	III		8.0	47	+44.9
(14)					?	45	+3.1
31			IV		*v*	44	−7.9
33			IV		*v*	43	−8.7
(15)			IV		?	42	−3.1
34	41.1903	c_0	IV		*v*	40	−18.1
			V		9.5	39	+36.8
(16)			IV		?	39	−2.1
			IV	74	13.7	39	−9.6
35	42.1903	c_2	V		*v*	38	+42.7 (6)
			IV	72	12.3	37	−11.4
36			IV		*v*	36	−14.8
			IV	15	8.8	36	−21.6
37			IV	66	*v*	34	−10.8 (2)
38					*v*	34	−23.7
			IV	73	13.3	32	−14.4
39			V		*v*	32	+34.6
(17)			IV		?	31	−2.9
40			V		*v*	30	+46.2
	−4°1185	*1	V		4.5	29	+37.9
41	43.1903	l_0	IV		*v*	29	−6.2
			IV	71	12.0	26	−2.4
42					*v*	26	+18.7
43					*v*	25	+17.4
44					*v*	24	+2.8
			IV	27	9.3	23	−19.8
			V		9.0	22	+34.5
45			V		*v*	22	+33.3
			IV	35	?	19	−4.5 (3)
			V		8.7	19	+39.0
(18)					?	19	−34.7
(19)			V		?	19	+39.6
46	83.1901	14	V		*v*	16	+27.3
48					*v*	16	+6.9
			VI	44	10.1	15	+16.8
	−4°1188	*2	V		6.0	12	+37.0
49				60	*v*	9	+0.3 (4)
50					*v*	9	+22.7
			VI	55	10.5	8	+8.7
			VI	62	10.9	8	+15.0
(20)					?	5	+0.4
51			V		*v*	4	+27.3
			VI	69	11.7	3	+12.0
52					*v*	2	−21.1
53				*T*	*v*	∓ 0	0.0
	8.1904	b_3	VI		*v*	0	+12.0
54	44.1903	a_0	V		*v*	1	+41.3
(21)					?	1	−23.2
55					*v*	2	+24.4
(22)					?	3	+2.1
(23)	84.1901	15	V		?	4	+31.6
			VI	21	9.1	+0 8	+6.3

P	Wolf		Chart	*A.S.V.*	Mag.	Δα	Δδ
(24)					?	$+0^m\ 9^s$	$-28'.9$
			V		9.5	9	+32.1
			V		9.5	10	+43.1
58					*v*	13	+46.9
63	85.1901	16	VI			25	+16.9
	−5°1335	*1	VI	19	*v*	37	+ 4.2 (5)
			VI	56	10.5	41	+ 5.4
(25)			VI		?	41	+11.6
65					*v*	47	+ 2.5
	−5°1338	*2	VI	17	9.0	48	+21.3
			VI	42	10.0	+0 49	+ 8.7

REMARKS.

(1) This is Bond's star 539, to which Pogson (*Second Madras Catalogue*, 1162) applied the name of *T Orionis*. In the *Cordoba General Catalogue* (6469) it is marked "var.," and it occurs in Chandler's *Catalogue III* under the suspected variables as No. (1980). (See *A. N.*, **163**, 117, Remarks to 1986.)

(2) In the Remarks of Pickering's *Circular* the variation of this star is described as small, but readily observed. When the chart for *T Orionis* was made, this star was marked as suspected of variability, on the ground of the following observations (expressed in the scale of the Atlas *Catalogue*):

1893, Dec. 12 (sky I): Step: 41, mag. 11.5.
1894, Jan. 12 (sky I): Step: 33, mag. 10.8.

(3) and (4) These two stars are Bond 746 and 784 respectively. Their variability was announced by Schmidt, but not confirmed by Chandler. In the latter's *Catalogue III* (note to No. 1986) several other stars are mentioned as probably variable, which do not occur in Professor Pickering's list.

(5) The variability of this star was suspected when the chart for *T Orionis* was made. About 180 estimates of brightness between the years 1891 and 1895 seem to indicate a period of 31 days and a fraction, but the variation is confined to the limits $9^m.0$ and $9^m.3$.

(6) The $\Delta\alpha$ of this star is taken from the publications of Pickering and Hartwig mentioned in the introduction. According to Wolf, $\Delta\alpha = -35^s$. However, Chart V will insure the identification of the variable.

GEORGETOWN COLLEGE OBSERVATORY,
April, 1904.

NOTE. — It is the author's intention to construct, for publication in this JOURNAL, a special chart based on the above list of stars, which will be available when the constellation of *Orion* can be again observed. — EDS.

OBSERVATIONS WITH THE BRUCE SPECTROGRAPH.

By EDWIN B. FROST and WALTER S. ADAMS.

FOUR STARS WHOSE RADIAL VELOCITIES VARY.

RECENT plates taken with the Bruce spectrograph have established the variation of the following stars having spectra of the *Orion* type. The number of stars of this type so far found with this instrument to be variable in their radial velocities thus becomes thirty-six.

9 *Camelopardi* ($\alpha = 4^h\ 44^m$; $\delta = +66°\ 10'$; Mag. = 4.4).

Plate	Date	G. M. T.	Taken by	Velocity		No. of Lines		Velocity Mean
				F.	A.	F.	A.	
				km	km			km
IB 194	1903, Nov. 17	$15^h\ 9^m$	A.	+14	+ 6	5	3	+10
229	Dec. 26	21 59	F.	+ 3	− 2	3	4	+ 1
254	1904, Jan. 2	21 30	A.	+01	+14	2	3	+12
	Second Component			− 9	− 6	2	2	− 8
285	1904, Feb. 26	17 10	A.	+ 9	+13	6	4	+11
	Second Component			+ 2	+ 3	2	2	+ 3
288	1904, Mar. 8	17 21	F.	− 6	− 7	3	5	− 7
	Second Component			+ 8	+ 6	2	2	+ 7
296	1904, Mar. 19	16 2	A.	− 1	+ 4	3	4	+ 2
	Second Component			−12	−12	2	2	−12

It was our first intention to include this star with the list of eight in our communication in the March number of this JOURNAL, but measures on the sharp and brilliant H and K lines gave results which were not accordant with the values derived from the remaining very diffuse lines in the spectrum, and publication was deferred until further plates were secured. The last four plates, which were exposed so as bring out well the region of H[1] and K, permitted excellent determinations of the radial velocity of the body producing those lines, and clearly show the existence of two components. Meanwhile Professor Hartmann's interesting article on δ *Orionis*, published in the May number of this JOURNAL, came to our attention. He finds that the K line in that spectroscopic binary does not share in the large radial velocity of the body in which the diffuse lines originate, and he believes that the K line does not "oscillate," attributing the range of 21 km in his measures to errors of observation. The K line on his plates of *δ Orionis* must be much less sharp than in the case of our star, which happens to show, so far, the same range of 20km (for the mean of the velocities of H and K). Here, however, the lines are so well defined that we can hardly think our determinations of the velocity from H and K (mean for the two observers) uncertain by more than 3km, to judge by the accordance of the independent measurements.

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[1] H is well separated from the adjacent hydrogen line *Hε*, so that the accuracy of the settings is not affected by the proximity.

κ Cancri ($\alpha = 9^h\ 2^m$; $\delta = +11°\ 4'$; Mag. = 5.0).

Plate	Date	G. M. T.	Taken by	Velocity		No. of Lines		Velocity Mean
				F.	A.	F.	A.	
				km	km			km
IB 256	1904, Jan. 2	$22^h\ 44^m$	A.	+ 2	+ 3	7	6	+ 2
267	Jan. 23	20 44	A.	+ 92	+ 84	4	5	+ 88
F 286	Feb. 26	18 38	A.	+ 37	+ 33	5	5	+ 35
	Second Component			−134	−136	1	1	−135
289	Mar. 8	18 36	F.	+ 82	+ 83	9	5	+ 83
	Second Compon't[1]			− 88	− 56	2	3	...
305	April 15	15 25	A.	+ 72	+ 68	4	5	+ 70
	Second Component			−105	− 90	2	2	− 97

The investigation of this star has proved of especial interest because of the presence of the second component. The lines in the case of the latter are very faint, and settings upon them are subject to considerable uncertainty, but their existence is unmistakable. The spectrum of the principal star has narrow, well-defined lines, particularly of hydrogen and magnesium, helium being very faintly represented. The spectrum of the second star seems to be of a similar type.

μ Sagittarii ($\alpha = 18^h\ 8^m$; $\delta = -21°\ 5'$; Mag. = 4.1).

Plate	Date	G. M. T.	Taken by	Velocity		No. of Lines		Velocity Mean
				F.	A.	F.	A.	
IB 311	1904, April 15	$20^h\ 36^m$	A.	+46	+45	5	5	+46
323	April 16	21 36	A.	+41	+43	5	8	+42
328	April 29	20 59	A.	....	−34	..	4	−34
335	April 30	21 4	F.	−34	....	4	..	−34

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[1] Measurements uncertain.

Two determinations by Wright of the motion of this star were published by Campbell in 1901 among examples of stars with large radial velocities.[1] The values were:

1899, June 19 - - - - - -	−75 km
1900, May 30 - - - - - -	−76 km

The close agreement of the two observations separated by an interval of nearly a year is a remarkable coincidence in view of the large range in the velocity. The spectrum is very similar to that of β *Orionis*, and the lines are well defined and narrow.

δ^1 *Lyrae* ($\alpha = 18^h\ 50^m$; $\delta = +36^\circ\ 51'$; Mag. $= 5.3$).

Plate	Date	G. M. T.	Taken by	Velocity		No. of Lines		Velocity Mean
				F.	A.	F.	A.	
				km	km			km
IB 298	1904, Mar. 19	$20^h\ 22^m$	A.	−79	−96	6	6	−88
308	April 15	18 40	A.	+ 6	+ 9	4	4	+ 7
319	April 16	19 00	A.	+ 4	+13	5	5	+ 8
325	April 29	18 32	A.	− 4	....	4	..	− 4

A plate taken on April 12 by F. shows a large difference as compared with the earlier plate. The exposure was stopped by clouds, however, and the plate is too weak for satisfactory measurement. The lines in this spectrum are diffuse and broad, and seem to be complicated by maxima. Accordingly considerable differences in the results of the two observers may well be expected.

RADIAL VELOCITY OF THE *Orion* NEBULA.

Our recent observations of the three brighter stars of the trapezium of *Orion* have furnished a number of determinations of the radial velocity of the nebula at the different points located by the positions of the stars. The bright nebular lines are superposed upon the spectrum of the star, in the case of the hydrogen lines δ, γ, and β overlying the broad and diffuse dark lines present in all the stars. This does not seem to disturb the accuracy of the settings upon the nebular lines, but the converse is not true, for the presence of the superposed bright lines renders it almost impossible to make a satisfactory setting on the dark star lines.

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[1] ASTROPHYSICAL JOURNAL, **13**, 90, 1901.

The plates utilized here were all taken with the dispersion of one prism and with a camera of 607mm (24 inches) focal length. While the greater scale of plates taken with three prisms would increase the accuracy of the measurements of the displacements of lines near the center of the field, this would here apply only to a single line, and the advantage would be more than offset by the greatly increased range of good focus (on some plates from λ 3970 to beyond λ 5000) on the one-prism plates. Furthermore, the exposure times required for obtaining the spectra of the stars (except θ^1) would be so long as to make the use of three prisms quite impracticable.

In the case of one exposure, for plate 287, on Bond 619, the "planet window" was used in front of the slit, and the nebular lines therefore extended out beyond the comparison lines, having a total length of about 2.6mm. This corresponds to an angular extent of 44″ in the sky. In this distance on the plate there is no evidence of a departure of the lines from the normal curve for the one-prism arrangement that would suggest any difference of radial velocities in that portion of the nebula included.

The comparison lines which were most frequently used for the different lines follow, with their (solar) wave-lengths according to Rowland. We have employed for the two principal nebular lines the wave-lengths as determined by Hartmann,[1] which yield values accordant with those obtained from the hydrogen lines. They are designated below as N_1 and N_2.

Line	*Hε*	*Hδ*	*Hγ*	*Hβ*	N_2	N_1
Adopted wave-lengths	3970.177	4101.89	4340.634	4861.527	4959.17	5007.04
Wave-length of comparison lines	*Fe* 3969.413	*Ti* 4078.631 *Ti* 4082.589 *Ti* 4099.327 *Ti* 4112.869	*Ti* 4338.084 *Ti* 4341.530 *Ti* 4344.451	*Ti* 4856.203 *Ti* 4870.323 *Ti* 4885.264	*Fe* 4957.785 *Ti* 4981.912	*Ti* 4999.689 *Ti* 5007.398 *Ti* 5014.369

The results obtained for the radial velocity of the nebula are collected in the following table, which probably requires no further words of explanation.

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[1] ASTROPHYSICAL JOURNAL, 15, 290, 1902.

Star	Plate	Date (G. M. T.)	Taken by	Velocity F.	Velocity A.	Lines Used F.	Lines Used A.	Velocity Mean
				km	km			km
θ^1 *Orionis*	IB 158	1903, Oct. 24.9	A.	+16	+21	γ, β, N_1	γ, β	+19
"	207	Dec. 1.8	F. A.	24	21	γ, β, N_1	γ, β, N_1	23
"	218	Dec. 25.7	A.	18	18	γ, β, N_2, N_1	γ, β, N_2, N_1	18
"	237	Dec. 27.7	A.	21	21	γ, β, N_2, N_1	γ, β, N_2, N_1	21
"	241	Dec. 31.7	F.	19	19	γ, β, N_1	γ, β, N_2, N_1	19
"	248	1904, Jan. 2.6	A.	15	16	γ, β, N_1,	γ, β, N_2, N_1	16
"	283	Feb. 26 6	F.	19	20	γ, β, N_1	γ, β, N_1	19
Bond 640	208	1903, Dec. 1.8	F. A.	15	17	γ, β, N_1	γ, β, N_1	16
"	249	1904, Jan. 2.7	A.	18	21	γ, β, N_2, N_1	$\delta, \gamma, \beta, N_2, N_1$	19
"	284	Feb. 26.6	A.	19	18	γ, β, N_2, N_1	γ, β, N_1	19
Bond 619	287	Mar. 8.6	F.	14	15	$\epsilon, \delta, \gamma, \beta, N_2, N_1$	$\delta, \gamma, \beta, N\ , N_1$	14

The mean velocity from these eleven plates is +18.5 km.

We cite for comparison the result of other observers as follows:

Keeler[1] (visual, with Lick star spectroscope) - -	1890–91	+17.7 km.
Wright[2] (Mills spectrograph) - - - -	1901	+16.2
Vogel and Eberhard[3] (Potsdam spectrograph IV) -	1902	+17.4

The low value we get from plate 287, at Bond 619, is rather surprising, as, on account of the excellent quality of the plate, a larger number of lines was measured than usual. We do not wish, however, to draw any inferences from a single plate, and our repeated attempts to secure additional plates this season have been defeated by cloudy weather.

Although our results can at this time be merely provisional in regard to the radial velocities of the three trapezium stars, it may be of interest in this connection to add the values so far obtained. We are not yet prepared to discuss the principal star θ^1 *Orionis*, the binary character of which was surmised by Sir William and Lady Huggins,[4] and confirmed by our observations communicated in the March number of this JOURNAL. The peculiarities of the spectrum are such that its proper discussion will require a large number of plates, and the radial velocity of the binary system cannot be given until the orbit is determined.

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[1] *Publications of the Lick Observatory*, 3, 217, 1894.

[2] ASTROPHYSICAL JOURNAL, 16, 58, 1902. [3] *Ibid.*, 15, 303, 1902.

[4] *Ibid.*, 6, 323, 1897, also, more fully, in their *Atlas of Representative Stellar Spectra*, pp. 138 142, 1899. We regret that we failed to allude to these observations in our previous article, but unfortunately they escaped us until after the JOURNAL had gone to press.

For the two other stars our results up to the present time can be given. Bond 640 is the following star, and Bond 619 the preceding star, of the four constituting the trapezium.

Bond 640.

Plate	Date	Taken by	Velocity		No. of Lines		Velocity Mean
			F.	A.	F.	A.	
			km	km			km
IB 208	1903, December 1	F. A.	+22	+18	5	4	+20
249	1904, January 2	A.	22	21	4	7	22
284	February 26	A.	17	18	4	5	18
						Mean	+20

Bond 619.

IB 287	1904, March 8	F.	+49	+46	7	8	+48
						Mean	+48

The rather large departure from the radial velocity of the nebula in the case of Bond 619 is interesting, but further plates will be required before any inference can be properly drawn. It is not at all impossible that this star varies in its radial velocity, like θ^1 and the neighboring star θ^2 *Orionis*. In that case we might expect that the radial velocity of the center of gravity of the binary would more nearly coincide with the velocity of the nebula.

THE RADIAL VELOCITY OF STAR C IN THE SYSTEM OF ζ *Cancri*.

The existence of irregularities in the motion of the faintest star in the triple system of ζ *Cancri* was investigated by Seeliger in 1881 on the basis of micrometer measures. He arrived at the conclusion that the star was attended by an invisible companion, and performed a revolution around their common center of gravity in a period of eighteen years. Two determinations have been made by A. of the radial velocity of the star, with a view to detecting such motion. These results are as follows:

C 9	1902, December 17	−12 km
IB 297	1904, March 19	−12 "

The number of lines measured in the two cases was eight and eleven respectively.

Accordingly there is no evidence of change in the star's motion during the interval of fifteen months between the two observations.

NOTE ON γ *Corvi.*

In *Lick Observatory Bulletin* No. 46[1] Messrs. Campbell and Curtis announce that the star γ *Corvi* varies in radial velocity, and give the values derived from six plates, which show a range of 24 km. This star was included in the list for which detailed observations were published in our recent paper on "Radial Velocities of Twenty Stars Having Spectra of the *Orion* Type."[2] It was our intention to exclude from that list all stars whose radial velocities varied, but our observations of this star happened to fall at such dates that no variation could be inferred. The range of velocity (mean for measures by F. and A.) was less than a kilometer for our three plates.

This star should therefore be excluded from the list in our Decennial paper, and its effect upon the mean for the twenty stars corrected. In averaging the proper motions of those stars it was omitted, owing to its relatively high value. Unfortunately our paper had been electrotyped before the Lick results were published, so that we were unable to make the necessary correction.

YERKES OBSERVATORY,
May 5, 1904.

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[1] ASTROPHYSICAL JOURNAL, **18**, 307, 1903.

[2] *Publications of the Yerkes Observatory*, **2**, 145–250, 1903.

REVERSALS IN THE SPECTRA OF SUN-SPOTS.

By WALTER M. MITCHELL.

IN observing the spectra of Sun-spots during the latter part of March and during April, a large number of lines were seen reversed. The first observation was on March 24 on a spot near the south following limb of the Sun. The second observation was made on March 30 on the same spot, which by this time had moved considerably past the center of the disk. The third observation was on April 15, on the large spot of the group which was visible during that week. The fourth and last observation was made on April 22, on a large spot on the north following limb. The spot had apparently come around a day or so before. For convenience the observations will be designated by (1), (2), (3), and (4).

On the first three dates the region of the spectrum observed extended from λ6600 in the red to λ5700 in the yellowish-green. On the fourth date the region observed was from λ6770 to C, and from λ6100 to F. All the observations on the last date were very unsatisfactory, the seeing was bad, and the spot, being very near the limb, presented a line instead of the usual round image.

All observations were made with the spectroscope of the 23-inch refractor of the Halsted Observatory, in the third-order spectrum of a Rowland grating of 4 × 2½ inches ruled surface—20,000 lines per inch.

In the whole region above mentioned from λ6770 to λ4915, over 270 lines have been observed as more or less affected in the spectra of Sun-spots. In the following preliminary list only the lines reversed are given.

The wave-lengths were read off from Rowland's photographic map, and afterward corrected to two decimals with the aid of Rowland's *Table of Solar Spectrum Wave-Lengths.*

In looking over the unpublished observations of Professors Young and T. Reed, made in 1892 with the same instrument, I have found that several of the lines were seen reversed at that time. These are indicated by a (Y).

Wave-Length	Element	Remarks
5250.39 s	*Fe*	(4) Reversed.
5432.75	*Mn*	(4) Strongly reversed.
5538.74	*Fe*	(4) Reversed.
5712.36	*Fe*	(1) Strongly reversed and on (4) medium reversal.
5727.87	*V?*	(4) Strongly reversed.
5731.48	*V*	(1) and (4) Strongly reversed.
5746.5 ?	....	(4) Strongly widened, reversed? There is apparently no corresponding dark line in the spectrum. Rowland gives an A line at λ 5746.64.
5748.57	*Ni*	(4) Medium reversal. (Y)
5781.13	*Cr–Ti*	(1) Medium reversal.
5781.40	*Cr*	(1) Strong reversal. (4) Medium reversal. (Y)
5781.97	*Cr*	(1) and (4) Much widened, strongly reversed. (Y)
5783.29	*Cr*	(1) and (4) Medium reversal. (Y)
5784.08 s	*Cr*	(1) Medium widening, but strong reversal. (Y)
5784.88	*Fe*	(1) Medium widening, but strong reversal; (4) Faintly widened, but still reversed. (Y)
5785.19	*Cr*	(1) Strong reversal. (4) Medium reversal. (Y)
5785.50	*Fe*	(1) Medium reversal.
5798.08 s	....	(4) Reversed ?
5880.83	*La ?*	(4) Strong reversal.
5910.20	*Fe*	(4) Strong reversal.
5918.77	*Ti*	(4) Strong reversal.
5938.04	....	(4) Strong reversal.
5958.46	....	(4) Strong reversal.
5999.92	*Ti*	(4) Medium reversal.
6002.97	....	(4) Reversed.
6005.77	*Fe*	(1) and (2) Medium widening reversed ? (3) and (4) Widened and reversed.
6008.19 s	*Fe*	(1) Medium reversal. (3) Reversed? (4) Strongly reversed.
6012.45	*Ni*	(1) Medium reversal. (2) Strongly reversed. (4) Faint, but reversed.
6013.72 s	*Mn*	(1) Slightly widened, reversed. (4) Medium reversal.
6016.86 s	*Mn*	(1) Slightly widened, reversed. (4) Medium reversal.
6039.05	*V*	(2) and (3) Strong reversal. (4) Medium reversal.
6064.85	*Ti*	(1) Wide reversal. (3) and (4) Strongly reversed.
6079.23 s	*Fe*	(1) and (2) Medium reversal. (3) and (4) Strong reversal. (Iron line at λ 6078.71 observed "widened" on (2) only. Not affected in any other observation.)
6081.67	*V*	(3) and (4) Strong reversal.
6082.93	*Fe*	(1) and (2) Strongly reversed. (3) and (4) Strong reversal extending into penumbra. (Y)
6085.47	*Ti-Fe*	(4) Medium reversal.
6089.79	*Fe*	(2) Fine thin reversal.
6090.43	*Fe–V ?*	(1) Strongly widened, reversed ? (4) Strong reversal.
6091.40	*Ti ?*	(4) Medium reversal.
6093.03	*Ti ?*	(4) Scarcely widened, but reversed.
6093.37	*Mn*	(3) and (4) Scarcely widened, but reversed.
6096.88	*Fe*	(3) and (4) Medium reversal.
6098.46	....	(3) and (4) Slightly widened, reversed.
6102.94 s	*Ca*	(1) and (4) Strong reversal.
6111.87	*V*	(3) Strongly reversed.
6126.44	*Ti*	(1) and (2) Medium reversal.
6129.19	*Ni*	(3) Slightly widened, reversed.

Wave-Length	Element	Remarks
6137.21	*Fe*	(1), (2), and (3) Strong reversal extending into penumbra. (Iron lines at λλ 6136.83 and 6137.92 not affected in any way on any date.)
6150.36	*V*	(1) Strongly reversed.
6151.83	*Fe*	(1) and (2) Strongly reversed. (3) Reversal extending into penumbra. (Y)
6151.44 s	*Na*	(1) Medium reversal. (4) Strong reversal.
6163.97	*Ca*	(3) Strongly widened, reversed ?
6173.55 s	*Fe*	(1) Strong reversal extending beyond umbra. (2) Strong reversal. (3) Strong reversal, possibly double reversal.
6188.21	*Fe*	(1) and (3) Medium reversal.
6240.86	*Fe*	(1) and (3) Medium widening, reversed ?
6243.06	*V*	(1) and (2) Medium reversal.
6243.32	*V*	(1) Strongly reversed. (3) Much widened, reversed ?
6246.54 s	*Fe*	(1) Medium reversal.
6252.05	*V*	(1) Strongly reversed.
6259.0	....	(1) Medium widening, reversed. (No corresponding dark line in spectrum.)
6266.55	*V*	(2) Seen widened. Reversed by (Y).
6285.38	*V*	(3) Medium reversal.
6302.71	*Fe*	(3) Strongly reversed.
6316.03	*Fe*	(3) Reversed ?
6327.82	*Ni*	(3) Medium reversal.
6330.31	*Cr*	(3) Reversed. (Y)
6337.05	*Fe*	(3) Medium reversal.
6363.09	*Cr–Fe*	(3) Medium reversal.
6380–6400	....	Spectrum of spot on April 15, resolved into 17 groups of fine lines (similar in appearance to G under low dispersion). Also observed by (Y).
6499.17	*Fe*	(3) Strongly widened, reversed.

In addition to the above lines observed reversed the following lines were seen diminished in width or "thinned."

6191.39 s	*Ni*	(3)
6432.89	*Fe ?*	(3)
6496.0 ?	*Fe*	(3) Appearance very similar, thinned or possibly a hazy reversal.
6496.69		
6546.48 s	*Ti–Fe*	(3)

In the region C–D the reversals are about 35 per cent. of the whole number of lines affected. About 5 per cent. more were observed "reversed ?" In this case the appearance was too uncertain to determine whether the line was reversed or not. The C line was observed partially reversed over a spot on April 8. The *b*'s, the E's, and the D's have not been affected in any way. The helium line D_3 was not visible in any observation.

The Observatory, Princeton, N. J.,
May 3, 1904.

RESEARCHES ON THE SYSTEM OF THE SPECTROSCOPIC BINARY β *AURIGAE*.[1]

By H. C. VOGEL.

THE discovery of spectroscopic binaries is in general possible only with the use of slit-spectographs of high dispersion, by means of the accurate measurement of the displacements of the lines of the stellar spectrum as compared with lines in the spectrum of a source of light at rest. The periodic variations of the component of the velocity in the line of sight then furnish the data for investigations on the orbits of the stars, even if only one component of the pair is visible. If the two components are of about equal brightness, a case which does not appear to occur often, a periodical displacement of the superposed spectra of the two bodies will be the result of their revolution, provided the plane of their motions is not too nearly perpendicular to the line of sight. Hence those lines which are due to elements which are present in the luminous atmospheres of the two heavenly bodies will be periodically doubled. In this case we may investigate the period of revolution as well as the further elements of the orbit of the binary on the basis merely of the measurements of the separation of the doubled lines; and if we forego the determination of the radial velocity of the system, a slit-spectrograph is not essential for the observation of such a binary; plates taken with objective-prisms are sufficient.

The second-magnitude star, β *Aurigae*, is one of the leading representatives of this class of spectroscopic binaries. To judge by the intensity of the spectrum lines, the two components are here equally bright, and the spectra of both bodies belong to the type I*a*2, having comparatively few lines.

The binary character of the star was discovered in 1890 in the course of the spectrographic *Durchmusterung* undertaken some fifteen years ago by E. C. Pickering at the Harvard College

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[1] Translated from advance proofs, sent by the author, of a paper to appear in the *Sitzungsberichte der Kgl. Akademie der Wissenschaften zu Berlin.*

Observatory.[1] The numerous photographs of the spectrum of this interesting star taken continuously there furnished further data for extensive investigation.

On the two dates, November 14, 1888, and January 3, 1889, a plate of the spectrum of the star was obtained at the Potsdam Observatory in the course of the researches on the motion of the stars in the line of sight conducted by myself during the years 1888 to 1891. On both plates are found two lines of almost equal intensity at the position of the magnesium line at λ4481. The spectrograms at that time covered only a small portion of the spectrum in the neighborhood of $H\gamma$, and in addition to this hydrogen line and the double line mentioned only a few extremely delicate lines could be recognized in the star's spectrum. To our limited knowledge of this region in stellar spectra at that time the occurrence of a double line presented nothing surprising, but if the spectrum had been repeatedly photographed the variation in the separation of the two lines could, however, not have been overlooked. As soon as the discovery of the binary nature of *β Aurigae* became known, five further plates of the spectrum were made at my request by Professor Scheiner, who was then assisting me in my observations, and on measuring these plates I was able to confirm most fully the results obtained at Cambridge. I collected my measurements and the conclusions derived from them in December 1890, and they were published in *Astronomische Nachrichten* (**126**, 265, 1891), and later (in 1892), with some additions, in Part I of the seventh volume of the *Publicationen* of the Astrophysical Observatory at Potsdam (pp. 139 *et seq.*).

I would here call especial attention to the fact that I then found that the relative intensities of the components of the *Mg* line at λ4481 were subject to change, since on some plates the component lying toward the red, and on others the component toward the violet, had slightly greater intensity. I further took pains to determine whether the masses of the two bodies could be regarded as nearly equal; or, in other words, whether the center of gravity of the system lay nearly midway between the

[1] HENRY DRAPER Memorial, Fourth Annual Report, 1890.

two bodies or nearer to one of them. The observations were rendered difficult by the fact that at that time hydrogen was the only comparison spectrum used on the plates. My studies led to the statement: "The agreement [of the measurements cited] leaves no doubt that the orbital velocities of the two bodies are only slightly different from each other at the time of greatest elongation" (*loc. cit.*, p. 143). I add here a few further paragraphs from this monograph (pp. 143 and 144).

> It would, in my opinion, be of little purpose to add here further observations as to the periodic doubling of the lines in the spectrum of *β Aurigae*, since the period of revolution of the two stars can be determined with great accuracy from the large amount of observational data collected at Cambridge. Pickering has given in the January number of the *Sidereal Messenger* for 1891 a short provisional statement as to the period yielded by the Cambridge observations, which was: Period of revolution $3^d\ 23^h\ 36^m.7$ ($3^d.9838$); lines in the spectrum single at approximately Greenwich mean noon on January 1, 1891.
>
> On the assumption that the greatest separation of the line corresponds to twenty-eight (German) geographical miles, I have computed back with this period to the Potsdam observations, and have found the best agreement on assuming January 1, 1891, 3^h G. M. T., for the epoch of single lines. (A table follows.) I would add for further characterization of the binary system, and for making complete the above statement, that on January 2, 1891, at 3^h G. M. T., the more refrangible of the separated lines was the stronger.
>
> On the assumption of a circular orbit with a slight inclination to the line of sight, taking the period as an even four days and the velocity as fifteen geographical miles, the separation of the two bodies would be 1,650,000 (German) geographical miles and the mass of the system would be 4.7 ⊙.

In describing a method of determining the orbit of spectroscopic binaries in the number of *Monthly Notices* for March 1891,[1] Mr. Rambaut derived for *β Aurigae* from the Cambridge observations a period of $3^d.968$ ($3^d\ 23^h\ 14^m$). He finds further that the orbit is an ellipse with an eccentricity $e = 0.156$, and he calculates the mean separation of the bodies as 7,500,000 (English) miles (in round numbers 12,000,000 kilometers).

The number of the ASTROPHYSICAL JOURNAL for October 1898[2] contains an article by Miss A. C. Maury, entitled "The K Lines of *β Aurigae*," in which it is stated that 200 spectrograms of this star were obtained at the Harvard Observatory in the nine years from 1889 to 1898. Observations were made with objective-prisms attached to the eleven-inch Draper telescope in each year, with the exception of the winter of 1896–7. Two prisms were used for 120 of the plates, while three and four prisms were used for the remaining 80 plates.

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[1] 51, 316. [2] 8, 171 *et seq.*

The following data are communicated as to the system: period = $3^d\ 23^h\ 37^m$; relative velocity = 240 km; distance of the two bodies = about 8,000,000 English miles, on the assumption that the line of sight is in the plane of the orbit; mass of the separate components = 1.25 ⊙. The period is therefore the same as that given by Pickering in 1891 in the *Sidereal Messenger.*

The main feature of the article is an investigation as to the relative intensity of the components of the K line. As I had previously announced in December 1890, the components of the *Mg* line at λ 4481 are subject to a variation in respect to their relative intensities, and in her examination of the great number of plates collected at Cambridge, which extend farther into the violet, Miss Maury found the same to be true for the K line (λ 3934), which is still stronger in the spectrum of *β Aurigae* than the *Mg* line. Unfortunately these investigations, and the conclusions from them, are in error, as I shall show below.

OCCASIONAL OBSERVATIONS OF *β Aurigae* AT THE POTSDAM OBSERVATORY.

Since 1891 only occasional plates of the spectrum have been obtained. Thus in 1897 Professor Hartmann made a few plates of the spectra of the brighter stars with the spectrograph of 1888 attached to the Schroeder refractor, and among these there is one plate of *β Aurigae* on which the *Mg* lines are separated. The component toward the violet is broader and more diffuse than the other, which renders the measurement difficult; and, on account of the unfavorable conditions under which it was taken, the plate is in any case of only slight reliability. I cite the observation, as it may nevertheless be utilized for confirming the correctness of the period derived below. The result was that on 1897, November 10.378, Central European Time, the relative motion of the components was 205 km per second.

For the same reason I mention here a few further plates secured with Spectrograph D in connection with the 33 cm photographic refractor. In spite of the low dispersion of this spectrograph, it is nevertheless possible to recognize with some certainty the phase of the component of the binary star. It is fortunate that the spectra extend far into the ultra-violet, and that the K line, which, as already mentioned, is sharp in the spectrum of β *Aurigae*, can be measured with some accuracy on account of the greater linear extent of the more refrangible regions in the prismatic spectrum.

The first plate was taken by Professor Wilsing for the spectrographic researches carried on by myself in conjunction with him.[1] The result was that on 1896, May 7.456, C. E. T., K was widely separated, corresponding to a relative velocity of 227 km.

The further plates with Spectrograph D were obtained by Drs. Eberhard and Ludendorff, who were engaged for a considerable time in an investigation of the most refrangible part of stellar spectra, for which its great light-power made instrument D especially suited. They extended their investigations as far as to λ 3550. The regions in the neighborhood of $H\gamma$ are greatly overexposed on all of the plates taken for the above purpose, and even the region around K is generally somewhat too long exposed. The plates were made with as narrow a slit as possible (0.01 mm), and the components of the K line are therefore very sharp and well measurable. I used various magnifying powers in making the measures.

1899	Relative Velocity	**Remarks**
March 5.50 C. E. T.	About 100 km	K appears as a broad line, perhaps double.
11.50	. . .	K single, broad.
12.43	. . .	K widely double. Plate overexposed.
12.40	212	K widely separated; very reliable measure.
14.40	217	Very reliable measure.
15.43	About 100	K perhaps double.
17.44	. . .	K pretty narrow and sharp.

Measurements show that the components were very nearly at the maximum separation on March 12 and 14. On account of the low dispersion, a separation of strong lines corresponding to a relative motion of 100 km could not be expected; hence the other spectrogram on which K is single would by no means necessarily represent the dates of perfect superposition of the lines.

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[1] *Publicationen des Astrophysikalischen Observatoriums*, **12**, 39, 1899.

After I had succeeded (from my measures of the numerous plates obtained by Messrs. Eberhard and Ludendorff with Spectrograph IV attached to the 33 cm refractor in the spring of 1901) in finally disentangling the relations in the spectrum of *ζ Ursae Majoris*,[1] which was discovered simultaneously with *β Aurigae* in 1890, and resembles it in respect to the doubling of the lines, my desire was aroused to again occupy myself with a thorough investigation of the system of *β Aurigae*. I therefore requested Professor Hartmann to obtain for the studies I had in view spectrograms of this star with Spectrograph I attached to the 80 cm refractor. The plates of other stars obtained by Professor Hartmann with this single-prism spectrograph extend far beyond K, and are remarkable for the fact that they possess an extraordinary and almost uniform sharpness over the whole region from $H\beta$ to $H\zeta$. Unfortunately, only four plates of *β Aurigae* were obtained on four successive days—on two days very nearly at the epoch of maximum separation, and on the other two at the epoch of minimum separation.

I now communicate my measures and observations on these very successful plates.

1901, September 23, 12^h 20^m C. E. T.—K is double, the lines being nearly equally broad, with the less refrangible one slightly the broader and somewhat less sharply bounded. The distance of the two lines was 0.662 rev. = 0.1655 mm, according to numerous measures made with different powers and with single and double threads, as well as with the plate in different positions under the microscope. In spite of their width and diffuseness, all the hydrogen lines from $H\beta$ to $H\zeta$ are clearly separated. The well-pronounced intensity-maximum can be set on quite accurately. But neither the $H\epsilon$ line nor the adjacent

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[1] *Sitzungsberichte der k. Akad. zu Berlin*, **24**, 534, 1901; ASTROPHYSICAL JOURNAL, **13**, 324, 1901.

Ca line are adapted for measurement, as the latter still falls within the shadow of the broad *Hε*. My measures give for the separation of the line 0.612 rev. for *Hδ*, and 0.480 rev. for *Hγ*, Numerous fine lines in the spectrum appear double.

A displacement of 1 rev. corresponds to a velocity of 334.1 km at K, 386.7 at *Hδ* and 464.4 at *Hγ*, whence we get for the relative velocity of the two bodies the values: 221 km(5), 237(2), and 223(1). The numbers in parentheses give the weights which I have assigned in averaging the values in the summary below. The decidedly large weight is given to K on account of its superior sharpness, the greater number of measures upon it, and the greater linear extent of the separation.

September 24, $13^{h}\ 17^{m}$ C. E. T.—The K line appears single, but very wide. From the measured width, combined with the measurements of the width of the separate components of the previous day, I determined the relative displacement to be 0.114 rev., although with only slight reliability (the four plates of *β Aurigae* were taken with the same slit-width and under favorable conditions, and the two spectra of each pair are so similar that they might be exchanged). Between *Hβ* and *Hζ* there can be seen on this spectrogram from 55 to 60 fine lines, many of which coincide with the lines of the iron spectrum.

September 25, $13^{h}\ 24^{m}$ C. E. T.—K is double, with the less refrangible component somewhat narrower than the other, though the difference is hardly appreciable. The separations and corresponding relative velocities are as follows: K (from many measures), 0.629 rev. = 210 km(5); *Hδ*, 0.557 rev. = 215 km(2); *Hγ*, 0.498 rev. = 231 km(1).

September 26, $12^{h}\ 52^{m}$ C. E. T.—K is central and with sharp edges, and is of almost the same width as on the spectrogram of September 24. The spectrum is very rich in fine lines, which appear more distinctly than on the plate of September 24. I could see 8 lines between *Hζ* and K, 5 between K and *Hε*, 14 between *Hε* and *Hδ*, 34 between *Hδ* and *Hγ*, and 16 in the somewhat overexposed portion of the spectrum from *Hγ* to λ 4550. I derived the relative motion of the two bodies as 46 km from measurements of a double iron line and from measures of the width of K.

The results of the measurements of the relative velocities of the components of the binary system on the four plates are accordingly

1901, Sept. 23.514 C. E. T.	225 km
24.553	38:
25.558	214
26.536	46:

As the star spectrum was inclosed by a comparison spectrum of iron, the radial velocity of the system could also be derived from the displacement of the K line, on the assumption that the components are of equal mass. The separate plates yielded the following values for the velocity of the system relatively to the Sun:

Sept. 23 =	−20.6 km
24	−14.0
25	−20.7
26	−14.1

In obtaining the displacement for September 23 and 25, when K was double, the mean was simply taken from the measures of the individual lines, and the components differed in phase by 180°. Hence we may conclude from the agreement of the two series of measures that the center of gravity of the system must actually have been situated very nearly centrally between the two bodies. This confirms my earlier observations above cited, which, of course, depend upon much less accurate material. It would appear surprising that the values agree in pairs, their means differing from each other by 6.6 km, which corresponds to a linear displacement of 0.005 mm on the plate. On September 24 and 26 the K lines are nevertheless no longer separated, but constitute a broad line, the center of which does not coincide with the middle point between the lines of which it is composed, if the components of the line differ in intensity and width. (I therefore give the observations of the two days a weight of two-thirds.)

The above observations having been made very nearly at the maximum and minimum separation of the lines, an appreciably different phase in the position of the body could not be expected for a considerable time, as the period was very nearly four days. The repetition of the observations, however, was finally given up, since it appeared that Hartmann's plates could be represented (purely accidentally, as turned out later) with Pickering's period from the zero epoch given by me as 1891 January 1, 3^h G. M. T. I therefore considered that the period required no serious corrections, since it was again employed by Miss Maury without change after the conclusion of the nine-year series of observations. My surprise was therefore not small when an article appeared in *Astronomische Nachrichten*[1] by Mr. G. A. Tikhoff, who on measuring the spectrograms of *β Aurigae* taken by Mr. Bélopolsky at the Pulkowa Observatory in 1902 and 1903, arrived at very peculiar results, wholly contradictory to the previous views.

ON THE DISCUSSION BY G. A. TIKHOFF OF THE SPECTROGRAMS MADE AT PULKOWA.

Mr. Tikhoff finds, in the first place, that the period of revolution of the two bodies is six minutes shorter (he gets $P = 3^d\,23^h\,30^m.4$) than Pickering had stated, and he suspects that it may have changed in the course of twelve years. This would not be unlikely, since he considers that *β Aurigae* must be regarded as a highly complicated system, consisting of four bodies instead of two. His curve representing the relative velocities during a period has the form shown in the figure. He explains it as the result of the superposition of two sine curves, one of which has the period just cited of nearly four days, while the other has a period exactly one-fifth of this ($19^h.1$). It is not at present possible to separate the two curves, as the combined curve is not yet sufficiently well known in all its parts. From the occasional doubling of the components of the single line which he perceived on some of the plates (for instance, on January 21, 1904, $H\gamma$ is resolved into four components having relative velocities, for the different combinations, of 1–2, 46 km; 1–3, 224 km; 3–4, 43 km; and 2–4, 221 km), Mr. Tikhoff arrived at the conclusion that *β Aurigae* is composed of two groups of bodies, each of which consists of a star with strong lines and a second star with weak lines. The period of revolution of the stars within each group is $19^{h}.1$, while each group completes a revolution about the center of gravity of the system in 3^{d} $23^{h}.5$. The ratio of the masses of the groups is nearly 1, and the center of gravity of the system has a radial velocity of — 16 km. Finally it is stated in the article that conjunction occurred on February 3, 1903, at 10^{h} Pulkowa M. T., and that on February 4 the component on the side toward red of the *Mg* line at λ4481 was

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[1] "Recherches sur les vitesses radiales de l'étoile *β Aurigae*," No. 3916.

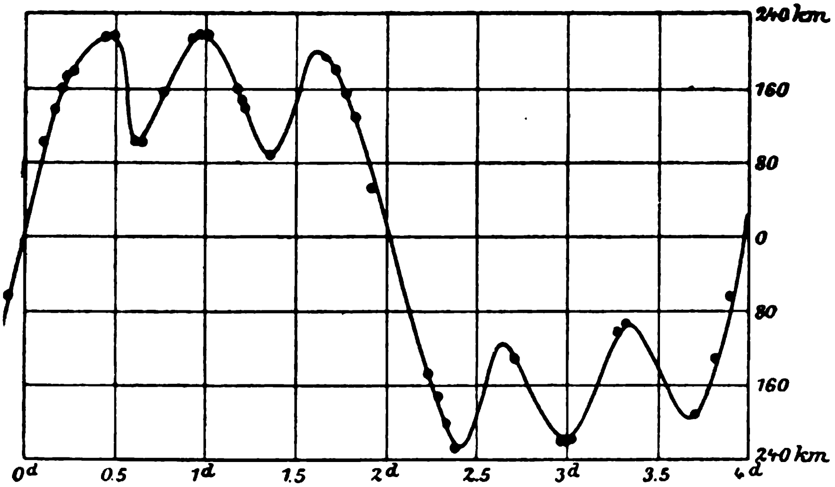

FIG. 1. — Velocity-Curve according to Tikhoff.

the stronger. I have previously observed such duplications of the components of the single lines in the spectrum of ζ *Ursae Majoris*, but it is entirely incomprehensible to me how they should cause precisely similar depressions in the velocity-curve at the two points of maximum, corresponding to a change of velocity of about 90 km.

Although I had to regard Mr. Tikhoff's conclusions from his observations as somewhat premature and certainly depending upon a very insecure foundation, I nevertheless felt that an immediate further examination of the relations in this binary system was a pressing necessity, and accordingly we began at once to obtain spectrograms of β *Aurigae*.

RECENT OBSERVATIONS AT THE POTSDAM OBSERVATORY.

The incredibly bad atmospheric conditions during last December defeated the earnest efforts of Drs. Eberhard and Ludendorff to quickly obtain the necessary data. The scattered observations did not permit any certainty as to the phase of the binary, and at the beginning of the year it could only be seen definitely that the observations so far obtained could not in any way be made to agree with Pickering's period. This somewhat disturbing condition was not broken until January 27, 1904 (the first and only continuously clear night from the middle of December until now), when it was possible to secure seventeen successive observations, and two observations on the next evening. Thus the time of the superposition of the spectra could be established with extreme accuracy, and from now on the observations could be represented by a period entirely different from that previously assumed. Later observations further confirm the fact that the period derived from the Cambridge observations was entirely incorrect. A period of 3^d960 furnished, first a satisfactory connection with Tikhoff's epoch of conjunction given above, and then with Hartmann's four plates in September 1901, and finally, with a small alteration of the period, with the epoch of superposition of spectra on January 1, 1891, that I had given. I further succeeded with a period

$$P = 3^{d}.9599 = 3^{d}\ 23^{h}\ 2^{m}\ 16^{s}$$

not only in representing all the earlier Potsdam observations, but also in recognizing the excellence of Tikhoff's measures, which neatly fitted a sine curve, and thus all the anomalies found by Tikhoff were made to disappear. The computations were all made by Dr. Schweydar with the formula

$$v = 222 \sin\left(\frac{t - t_0}{P} \times 360^\circ\right),$$

where P is the period just given, 222 km represents the maximum separation of the lines, and t_0 is taken as 1904, January 27.750, Central European Time.

Tikhoff's observations fit this formula as perfectly as is possible in view of the uncertainty of measurement of the lines in such spectra, which are not easy to set upon; and the beautiful set of observed data furnished by him makes it possible definitively to conclude the investigations on β *Aurigae* at this time, in so far as they refer to the determination of the orbit, the masses, and the radial velocity of the system.

Further investigations would be desirable to clear up the matter of the continuous change in the appearance of the lines in the spectra of such binaries, but these should be made only under the most favorable conditions and with very high dispersion. I shall take up this point more in particular later, but will now give here the results of my measures on the plates taken with Spectograph IV attached to the 33cm refractor by Drs. Eberhard and Ludendorff, working either together or in alternation.

No.	Date C. E. T.	*Mg*	*Ti*	Mean	Quality	Computed	C.-O.	Remarks
		km	km	km		km	km	
1	1903, Dec. 22.315	217	213	215	1-2	212	− 3	
2	24.230	210	220	218	1-2	217	− 1	
3	25.304	71	77	74	1	74	0	
4	27.275	56:	55:(½)	56:	½-1	71	+15	
5	28.291	200	190(½)	197	½-1	207	+10	Comp. *Mg*, *Ti* double
6	29.364	107	109(⅔)	108	½-1	106	− 2	
7	31.208	59		59	½ 1	62	+ 3	
8	1904, Jan. 4.211	74	62(¼)	71	1	76	+ 5	
9	5.330	185	182	183	2	189	+ 6	Comp. *Hγ*, *Mg*, *Ti* double
10	6.226	96:	75:(2)	82:	1	87	+ 5	
11	10.274	131	131	117*	1	115	− 2	Comp. *Mg*, *Ti* double
12	.472	183		183	1	168	15	
13	17.323	171	183	177	2	165	− 12	Comp. *Hγ*, *Mg?*, *Ti* double
14	.398	147	145	146	2	140	0	
15	519	133	125	129	1-2	111	18	
16	19.457	134	137(½)	135	1	124	11	
17	27.224	169	171	170	2	165	− 5	
18	.248	153		153	½-1	159	+ 6	Comp. *Mg*, very unequal; *Hγ*, *Mg* double
19	.275	162		162	1	152	− 10	
20	.298	160		160	½	144	16	
21	.323	151	153	152	1-2	139	−13	
22	.345	137		137	1	133	− 4	
23	.368	141	140	141	½ 1	126	−15	
24	.390	124		124	½-1	120	− 4	2. Comp. *Mg* very diffuse.
25	.412	127	130	128	1 2	114	−14	
26	.435	115		115	½-1	106	− 9	Comp. *Mg* very unequal
27	.457	111		111	½	100	−11	
28	.482	109	94	102	½	92	−10	
29	.535	67	68	68	1	74	+ 6	
30	.557	60	60	60	1	67	+ 7	
31	.578	43	56	50	1	60	+10	
32	.603	67	59	63	1	51	12	
33	.633	27	40	34	1	41	+ 7	
34	28.234	158		158	1	154	4	
35	.335	187		187	1	178	9	
36	30 240	160	156	158	1-2	161	+ 3	
37	.202	165	164	165	1-2	160	+ 1	
38	.282	164		164	½	171	+ 7	
39	Feb. 9.350	199		199	1	202	+ 3	

NOTES.—The third column contains the relative velocities as derived from the observations of the *Mg* line at λ 4481. The dispersion of the apparatus is such that the displacement of one revolution of the screw (0.25 mm pitch) of the measuring machine corresponds to a velocity of 341.7 km. Column 4 contains the results of the measurements of a line very well defined on several plates, the wave-length of which I have determined to be 4549.69; since this is probably to be identified with the titanium line, the column has been headed *Ti*. In this region of the spectrum 1 rev. = 365.3 km. The measures on the *Ti* line are often of somewhat less weight than those on the *Mg* line, and the numbers in parentheses after certain values are the weights assigned in forming the mean given in column 5. A colon (:) indicates that the value is somewhat uncertain. The asterisk (*) at the eleventh plate denotes that in this case a very reliable measurement could be made of the separation of the double *Fe* line at λ 4326, which yielded a velocity of 102 km (2). Column 6 contains estimates as to the quality of the observations, the best plates being denoted by 2.

The deviations of the observations from the sine curve average from 7 to 8 km with the negative values in excess by — 3 km

No.	Date C. E. T.	Obs. Vel. Tikhoff	Comp. Vel.	C.—O.
		km	km	km
1	1902, Feb. 14.421	161	146	—15
2	15.388	160	172	+12
3	19.406	145	159	+14
4	26.381	173	166	— 7
5	26.410	180	173	— 7
6	27.379	142	145	+ 3
7	Mar. 4.401	172	184	+12
8	5.415	102	118	+16
9	11.448	84	89	+ 5
10	12.396	200	197	— 3
11	13.396	96	99	+ 3
12	24.407	228	214	—14
13	April 7.399	218	222	+ 4
14	7.427	218	222	+ 4
15	Nov. 15.517	191	193	+ 2
16	16.442	100	89	—11
17	17.438	198	202	+ 4
18	25.472	176	183	+ 7
19	26.454	131	124	— 7
20	Dec. 9.502	133	142	+ 9
21	11.445	154	152	— 2
22	14.417	155	162	+ 7
23	19.443	128	131	+ 3
24	1903, Jan. 18.371	65	59	— 6
25	19.406	216	218	+ 2
26	20.383	49	47	— 2
27	21.403	217	219	+ 2
28	23.408	219	220	+ 1
29	24.373	Single, broad	37	....
30	25.429	221	222	+ 1
31	31.398	218	222	+ 4
32	Feb. 3.403	Single, broad	8	....
33	10.375	217	221	+ 4
34	Mar. 11.296	102	95	— 7
35	21.379	147	148	+ 1
36	27.276	140	137	— 3

in the sense C.—O. As the larger values are mostly situated on the descending branch of the curve, they indicate that the descent of a curve drawn directly through the observed points is somewhat steeper than the ascent. If we wished to regard these slight deviations as real, we should be justified in concluding that the orbit was slightly elliptical. The probable error of the measures on one plate is ± 6 km.

Tikhoff's measures, shown above (p. 372), fit the sine curve still more closely.

The deviations of the measured velocities from those represented by the curve average 6 km, the negative and positive values nearly canceling (mean + 1 km). The probable error comes out as ± 5 km, so that the determinations are superior in accuracy to mine. This is accounted for by the facts that I limited my measures to the *Mg* line and the *Ti* line, while Mr. Tikhoff measured several lines on each plate, and that about half of the spectrograms used by him were made with a spectrograph of larger dimensions.

The epoch 1903, February 3, 8^h 59^m, given by Tikhoff for the superposition of the spectra, or for the conjunction of the components of the binary, is computed by the above formula to be February 3 9^h 6^m C. E. T.

I now return to the Potsdam observations of earlier years. The relative radial velocities computed from the above formula with the residuals in the sense C.—O. are as follows for the observations in 1901:

Sept. 23.514	220 km,	− 5 km	Sept. 25.558	215 km,	+ 1 km
24.553	49	+ 11	26.536	50	+ 4

On similarly computing the values for the dates in 1899 on which the spectrograms were obtained with the low-dispersion spectrograph D, we get these velocities:

March 5.5,	119 km	March 14.46	196 km
11.5,	101	15.43	111
12.43,	187	17.44	101
12.49,	198		

A comparison of the observations shows that they are not contradictory to the computation, which is also true for the isolated observation made with the same instrument on 1896, May 7.456. The computed separation of the lines corresponds to a relative velocity of 216km.

Finally, the first observations made here for determining the radial velocity of stars with the spectrograph I designed in 1888 also fit the computed values as well as could be expected when we consider that these plates are in general less sharp, and that further the *Mg* line λ4481 was situated outside the region of sharp definition of the camera objective. I have measured the plates again, but could not get any appreciably different *Auffassung*. On the plate of December 6, 1890, I was able with favorable illumination to see the separate components of the broad *Mg* line and to measure their separation. I give the observations here, together with the isolated observation taken in 1897 with the same instrument:

Date		Measure			Computed	C.–O.
		Former	New	Mean		
		km	km	km	km	km
1888, Nov.	14.424	188	181	185	146	−39
1889, Jan.	3.276	194	204	199	213	+14
1890, Nov.	22.401	30:	35	33	32	− 1
	25.410	212	218	215	221	+ 6
	26.428	(Single)	0:	0:	8	+ 8:
Dec.	14.338	(Single)	37	37	24	−13
	21.281	205	207	206	220	+14
1897, Nov.	10.378	....	205	205	190	−15

NOTES.—The observations can be somewhat better fitted to the curve by increasing the period by three units of the fifth decimal, or by 3ˢ. We then get the following deviations of the separate observations in the sense C.-O.: −30km, +17, −13, +7, +4, −1, +12, and −12km. On further increasing the period the observations are not so well represented.

The time at which the spectral lines appeared single on January 1, 1891, is computed by the new formula to be $2^h\ 11^m$ C.E.T., while I formerly derived from the first seven observations, 1891, January 1, 3^h, G.M.T., or 4^h C.E.T.

I believe that after all these tests the correctness of the formula given may be considered as proved, and I regard the period as accurate within a few units of the fifth decimal or $\pm{}^{\cdot}5^s$, since the observations cover about 14 periods.

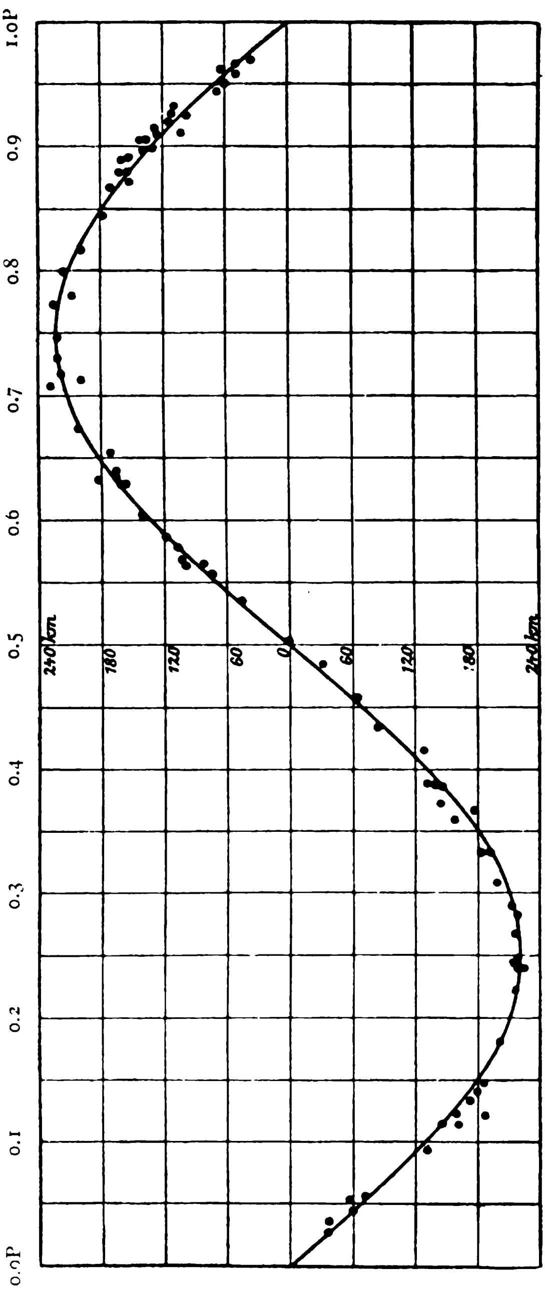

FIG. 2.—Velocity-Curve of *β Aurigae* according to Vogel.

The accompanying diagram shows that the eighty-five observations fall upon all parts of the curve, and that the deviations are only very slight from the sine curve and hence from a circular orbit. The eccentricity, if any should be established with certainty by later observations, would hardly exceed 0.05, so that Rambaut's early value of 0.156 is not confirmed.

On the assumption of a circular orbit, a relative velocity of the two bodies of 222 km, and the period derived above of $3^d.9599$, the result of the mass for the system is

$$m + m_1 = \frac{4.5 \odot}{\sin^3 i},$$

and the distance of the two bodies comes out as

$$a \sin i = 12 \text{ million km.}^{1}$$

(The discrepant value of 1.25⊙ for the mass of each of the components given by Miss Maury in the article referred to above is probably due to an error of the pen or of the type.)

As was shown above, and as is further confirmed by the following observations as to the radial velocity of the system, the masses of the two components of the system are not very different from each other.

RADIAL VELOCITY OF THE SYSTEM.

By referring the measures of the *Mg* line to the *Fe* comparison spectrum I have derived the motion of the system in the line of sight from the Potsdam observations of 1903 and 1904, and I find as the mean of the observations on thirty-five plates the value:

$$-21 \pm 1 \text{ km.}$$

---

[1] Since no variation has been thus far observed in the brightness of *β Aurigae*, so that a partial occultation of the bodies does not occur, the maximum value for the angle i included between the line of sight and the perpendicular to the plane of the orbit can be computed if we make further assumptions as to the diameters of the two bodies. In view of the early stage of development of stars of class Ia2, we may doubtless assume that their density is less than that of the Sun. If we take the diameters of the components of *β Aurigae* to be twice that of the Sun, we get $i = 77°$, and then $a = 12{,}400{,}000$ km, and $m + m_1 = 4.9 \odot$. For $i = 60$ these values increase decidedly, so that a becomes in round numbers 14,000,000 km, and the masses become $6.9 \odot$.

This value agrees well with that of —19 found by M. Deslandres in 1892, with that of —18 given by the four Potsdam plates of 1901, and with that of —16km determined by Tikhoff. In deriving the velocity of the system the displacement of the center of the separated *Mg* lines is obtained by reference to the *Fe* lines, and if the center of gravity did not fall very nearly midway between the two bodies, variations in the values thus obtained for the amount of displacement would have to appear as a result of the motion of the system. The variations among the separate values are not greater, however, than would be expected for the difficultly observable *Mg* line.

The observations in one half of the orbit, between the points where the lines are superposed, give a mean value for the velocity of the system of —19.4km, and for the other half of the orbit of —22.7km.

The near equality in the masses of the two component systems can be further confirmed by the direct computation of the velocity of the separate bodies relative to the Sun from the displacement of the *Mg* lines as compared with the lines of the comparison spectrum. A computation and graphic representation by Dr. Schweydar shows that one and the same sine curve represents very well the velocities found for each body, on the assumption of a maximum velocity of 111 km.

ON THE PERIODIC CHANGES IN THE APPEARANCE OF THE LINES.

As I have stated above, I noticed during the earliest observations that one component of the *Mg* line appeared broader, somewhat more diffuse, and probably also somewhat stronger than the other, and that a change took place in that first the stronger and then the fainter component fell further toward the red. This observation suggested the idea that the spectrum of one of the bodies was somewhat more intense than that of the other, and that the change stood in relation to the position of the bodies in their orbit.

The few observations then available were not sufficient to make the matter certain, but as I had no reason for doubting the correctness of this assumption, I characterized the appearance of the spectrum by the statement: "On January 2, 1891, the more refrangible component of the *Mg* lines is the stronger." (See above.)

Mr. Tikhoff must have taken a quite similar point of view, since he states, in an expression analogous to that I made twelve years ago: "On February 4, 1903, the strongest component of the *Mg* line is the least refrangible." Unfortunately no remarks are added to his observations as to the relative intensity of the components; otherwise it would have been possible for me to decide, on the basis of the correct period, whether or not a change of the intensities actually occurs after each conjunction. Such a change must occur if the lines in the spectrum of one of the bodies are invariably stronger than in the other, but it would not occur if the change were purely accidental.

I have not been able to prove the fact of any regular change dependent upon the orbital position of the bodies; but, on the contrary, have been convinced by the recent observations, particularly by the continuous series of plates made on the night of January 27-28 of this year, that the change occurs wholly irregularly.

A change in the relative intensity of the components of the *Mg* lines also occurs in the case of *ζ Ursae Majoris*, but it has been just as impossible for me, as in the case of *β Aurigae*, to discover a relation with the phase at which the bodies composing the binary system are situated at the time.

In her article, which I mentioned at the beginning of this paper, Miss Maury made a summary by counting the plates in one year on which the component of K toward the red was the stronger, and obtaining the number of those for which the opposite was true, and the number of those in which both components appeared equally strong. She finds a change in the relative intensity on the plates, which cover a period of nine years, to the effect that a reversal occurs every year; that is, that the relative intensities of the components of K behave during one year in just the opposite manner to that of the preceding year.

Now it is easy to see that such statistics cannot lead to any useful results unless they are made out in connection with a curve representing the observations. For, assuming that a change actually occurs after every conjunction, it might chance that in one year the greater number of the plates were photographed at a time when the stars were situated in the first half of the orbit between two conjunctions, but in the next year, in the second half of the orbit. The only thing of interest that can be taken from the table is the number of cases in which the components appear equally strong, which on the average constitute only 17 per cent. of all the observations.

The magnitude of the variations of intensity of the *Mg* line, to which my observations principally refer, is often very considerable. On some plates the one component is sharp, very distinct, and well defined, while the other is, on the contrary, very broad, diffuse, and so faint that its position can be measured only with difficulty. Sometimes one line will appear double, and sometimes both; they then consist either of a broad and a very narrow line, or of two equally broad lines, whose separation corresponds to a relative velocity of 40 to 50 km. The *Mg* and *Ti* lines often agree entirely, but more frequently they are wholly different. The hydrogen line *H*γ appears distinctly quadruple on some plates, and there sometimes occur in the spectrum new lines, single, and often quite sharp, for which no components can be found, while the *Mg* lines are separated.

These are all phenomena which I have already also observed in the spectrum of ζ *Ursae Majoris*. I quote here a passage referring to this matter from my second paper[1] on that star:

> I have already spoken in my first paper on the observations of *Mizar* as to the variation in appearance of the components of the *Mg* line on different plates. The further observations have not made it possible to decide that the variations bear a relation to the period.
>
> It is seldom that the components of the *Mg* line are equal in respect to intensity and width, and commonly the more refrangible of the components is the broader. No change in the appearance can be definitely proved after the superposition of the spectra. Some of the recent observations show both

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[1] First paper, *Berlin Sitzungsberichte*, 1901, **24**, 534 *et seq.*, ASTROPHYSICAL JOURNAL, **13**, 324–328, 1901; second paper, "Weitere Untersuchungen über das spectroscopische Doppelsternsystem *Mizar*," *Archives Néerlandaises*, Haarlem, 1901, 661 *et seq.*

components to be themselves double, in which case the lines of the two pairs are very sharp and narrow. It does not seem possible to regard these inequalities as due to accidental changes in the grain of the photographic film, since similar variations are occasionally exhibited in the case of some of the iron lines, although this is of less certainty on account of the faintness of the lines. The assumption does not seem to me, however, to be unlikely that the great variation in the separation of the two bodies during their orbital motion (from 16 to 51 million kilometers) may cause mutual disturbances in the atmospheres of the bodies which at times might produce phenomena of reversals or of broadening of the lines.

Although it seems justifiable to assume the existence of such disturbances in the atmospheres in the case of *Mizar* with its strongly elliptical orbit ($e = 0.502$), in the present case of an almost circular orbit, there is no basis for such an assumption.

The view expressed by Tikhoff that each of the components is also a double star cannot be directly denied, but in my opinion it receives no support from the similar behavior of the lines of *Mizar.* I would therefore call attention to the following reasoning.

The spectra of class Ia2 show only a greater or less number of quite faint lines aside from the broad lines of hydrogen, calcium, magnesium, iron, and titanium. The continuous spectrum of *β Aurigae* seems at the time of perfect or almost perfect superposition of the two spectra to be crossed by a very large number of fine lines, so that the continuous spectrum gets the appearance of a fine parallel structure irresolvable at some points. When two such spectra are brought one upon the other by the displacement, the lines of the one spectrum are projected upon the by no means uniform spectral background, and thus lines which would be scarcely recognizable in a single spectrum can and must suddenly appear to be greatly strengthened; but others will be very much weakened if they fall upon one of the brighter portions of the superposed spectrum.[1] I am of the opinion that this may possibly also explain the occasional duplication, and the change of the relative intensity or of the sharpness of the broad separated *Mg* and *Ti* lines or of the K line. The additional circumstance enters that with the possible exception of calcium, the absorption is not very strong in the atmosphere of bodies of class I*a*2, so that in general the superposition of two spectra will cause the lines to be brightened up to some extent, if the spectra are not in perfect coincidence. It is on account of this that the success of spectrograms of such spectra is so very dependent upon the correct exposure. There can be no doubt, further, that the structure of the photographic film here plays a much more important part than in the case of plates of spectra which are not superposed.

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[1] I was led to this opinion by the results obtained on using the method suggested by Mr. Bélopolsky, of Pulkowa, for making very faint lines in spectra better visible. The method consists in laying two spectrograms of the same object over each other so that the principal lines coincide. Faint lines then come out very clearly, and if a photograph is made of these superposed plates, the lines of this new spectrogram can be still further strengthened by placing over it one of the first plates.

Only spectrograms obtained with very high dispersion on plates of the finest possible grain can be employed for establishing the cause of these phenomena. It will be necessary to secure frequent plates at short intervals and to compare the variations of the *Mg* line at λ4481 with those of other lines.

POTSDAM, March 1904.

LINE OF SIGHT CONSTANTS FOR SOME STARS OF THE *ORION* TYPE.

By EMILY ELISABETH DOBBIN.

THE line-of-sight constants for the following 112 stars of the *Orion* type were computed for the reduction of observations made with the Bruce spectrograph at the Yerkes Observatory, upon which the writer has been engaged during recent months. The formulæ employed by Dr. Frank Schlesinger in his "Line of Sight Constants for the Principal Stars"[1] were used, and the arrangement of the results is the same, with the minor exceptions that the latitude of the star is omitted and the right ascension and declination are added. The stars are taken from the regular observing program made out by Professor Frost from the lists of Vogel and Wilsing,[2] and of Miss Maury and Miss Cannon.[3] But those stars are omitted which were already included in Schlesinger's list. The magnitudes of the stars are for the most part taken from the *Harvard Photometry*.

In bringing the positions of the stars to the epoch 1900, no correction for proper motion was made. The constants for about forty of the stars were first computed by Mr. H. A. Fisher, Jr., but these have been repeated. All the results here collected were derived twice independently.

For the sake of completeness, the formulæ are repeated here. The correction x, to compensate for the orbital velocity of the Earth, is

$$x = b \sin (\odot - \lambda) + c \ .$$

Of course, λ must be corrected for the precession since 1900 to the beginning of the year for which it is required, by the addition of 50″ per year. λ, b, and c were derived from the formulæ

$$\tan \lambda = [9.96255] \tan \alpha + [9.59987] \sec \alpha \tan \delta \ ,$$

$$b = [1.47371] \sec \lambda \cos \alpha \cos \delta \ ,$$

$$c = [8.224] \, b \sin (281^\circ \, 20' - \lambda) \ .$$

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[1] ASTROPHYSICAL JOURNAL, **10**, 1, 1899.

[2] *Publicationen des Astrophysikalischen Observatoriums zu Potsdam*, **12**, 1–73, 1899.

[3] *Annals of Harvard College Observatory*, **28**, 1897 and 1901.

Star	Mag.	R. A.	Dec.	λ (1900)	log *b*	*c*
49 *Cassiopeiae*	5.0	$0^h\ 30^m\ 34^s$	+53° 37′.0	33° 44′.8	1.3232	−0.33
ξ *Cassiopeiae*	4.9	0 36 29	+49 57.9	32 05.4	1.3486	−0.35
68 *Cassiopeiae*	5.5	0 38 53	+47 19.0	30 45.0	1.3644	−0.37
ν *Andromedae*	4.4	0 44 18	+40 32.0	27 45.6	1.3995	−0.40
146 *Cassiopeiae*	5.5	0 50 45	+59 49.3	42 14.5	1.2949	−0.28
α *Sculptoris*	4.1	0 53 47	−29 53.9	359 05.2	1.3997	−0.41
g Persei	5.0	1 55 38	+54 00.3	48 33.2	1.3643	−0.31
35 *Arietis*	4.5	2 37 35	+27 16.9	45 32.4	1.4652	−0.40
B. D. 51°665 *Persei*	5.2	2 53 44	+51 57.3	57 29.2	1.3942	−0.29
1 Hev. *Camelopardi*	4.8	3 11 11	+65 17.2	66 29.4	1.3213	−0.20
29 *Persei*	5.3	3 11 30	+49 51.4	59 47.8	1.4080	−0.28
τ *Arietis*	5.2	3 15 27	+20 47.2	51 59.9	1.4733	−0.38
B. D. 48°899 *Persei*	5.2	3 16 08	+48 51.4	60 16.4	1.4132	−0.28
2 Hev. *Camelopardi*	4.2	3 20 58	+59 35.6	65 11.3	1.3610	−0.23
3 Hev. *Camelopardi*	4.7	3 21 55	+58 32.0	64 53.6	1.3674	−0.23
34 *Persei*	4.8	3 22 13	+49 09.8	61 28.4	1.4132	−0.28
τ^5 *Eridani*	4.2	3 29 22	−21 58.1	42 47.9	1.3614	−0.33
40 *Persei*	5.0	3 36 02	+33 38.7	59 44.2	1.4608	−0.32
q Tauri	4.3	3 39 15	+24 09.2	58 10.1	1.4724	−0.34
20 *Tauri*	5.0	3 39 52	+24 03.4	58 17.0	1.4724	−0.34
c Tauri	5.0	3 42 47	+10 50.2	55 57.0	1.4687	−0.35
τ^8 *Eridani*	4.7	3 49 27	−24 54.4	47 27.6	1.3331	−0.29
B. D. 34°768 *Persei*	5.5	3 50 02	+34 47.4	62 54.7	1.4599	−0.30
40 *Tauri*	5.3	3 58 26	+ 5 09.6	58 33.2	1.4586	−0.33
μ *Tauri*	4.3	4 10 06	+ 8 38.5	62 11.0	1.4638	−0.31
d Persei	4.9	4 14 19	+46 15.6	70 13.3	1.4324	−0.23
τ *Tauri*	4.3	4 36 14	+22 45.9	70 45.4	1.4737	−0.25
μ *Eridani*	4.0	4 40 30	− 3 26.3	67 56.3	1.4296	−0.25
9 *Camelopardi*	4.4	4 44 06	+66 10.4	79 35.0	1.3349	−0.13
π^4 *Orionis*	4.0	4 45 53	+ 5 26.1	70 42.2	1.4548	−0.24
ψ *Eridani*	4.8	4 56 35	− 7 19.1	71 48.6	1.4122	−0.21
B. D. 34°980 *Aurigae*	5.9	5 09 42	+34 11.9	79 25.2	1.4653	−0.18
τ *Orionis*	3.6	5 12 45	− 6 57.2	76 27.0	1.4119	−0.18
ο 22 *Orionis*	4.0	5 16 39	− 0 28.9	78 10.4	1.4362	−0.18
25 *Orionis*	4.8	5 19 33	+ 1 45.3	79 08.6	1.4429	−0.18
ψ *Orionis*	4.7	5 21 36	+ 3 00.6	79 47.1	1.4464	−0.17
A Orionis	4.0	5 25 26	− 5 52.4	80 59.6	1.4535	−0.16
χ *Aurigae*	5.0	5 26 13	+32 07.1	82 46.0	1.4685	−0.16
υ 36 *Orionis*	4.5	5 27 06	− 7 22.4	80 31.0	1.4088	0.15
35 *Orionis*	5.7	5 28 13	+14 14.2	82 12.2	1.4683	−0.16
ϕ^1 *Orionis*	4.6	5 29 20	+ 9 25.3	82 12.6	1.4609	−0.16
S. D.−6°1233 *Orionis*	4.5	5 30 09	− 6 04.1	81 29.1	1.4143	−0.15
Bond 619 *Orionis*	7	5 30 21	− 5 27.2	81 34.9	1.4168	−0.15
Bond 624 *Orionis*	8	5 30 22	5 27.1	81 35.0	1.4168	−0.15
Bond 640 *Orionis*	7	5 30 23	− 5 27.2	81 35.3	1.4168	−0.15
θ^1 *Orionis*	4.6	5 30 22	− 5 27.3	81 35.1	1.4166	−0.15
c^1 *Orionis*	4.7	5 30 27	− 4 54.2	81 38.8	1.4191	−0.15
θ^2 *Orionis*	5.3	5 30 28	− 5 28.9	81 36.8	1.4167	−0.15
ω *Orionis*	4.5	5 33 54	+ 4 03.9	83 06.4	1.4488	−0.15
S. D.−3°1167 *Orionis*	6.0	5 34 32	− 3 37.2	82 52.3	1.4239	−0.14
S. D.−1°1004 *Orionis*	4.9	5 35 46	1 10.9	83 20.5	1.4327	−0.14
57 *Orionis*	5.8	5 49 02	+19 43.8	87 24.7	1.4728	−0.12
139 *Tauri*	5.0	5 51 47	+25 56.4	88 09.2	1.3731	−0.09
64 *Orionis*	5.1	5 57 32	+19 41.6	89 25.1	1.4728	−0.10
χ^2 *Orionis*	4.8	5 57 59	+20 08.4	89 31.5	1.4729	−0.10
ν *Orionis*	4.7	6 01 52	+14 46.8	90 27.3	1.4688	−0.09
ξ *Orionis*	4.4	6 06 15	+14 13.9	91 32.2	1.4680	−0.08
f^1 *Orionis*	4.8	6 06 17	+16 09.2	91 31.3	1.4702	−0.08
S. D.−6°1446 *Monocerotis*	5.1	6 07 00	− 6 31.6	92 00.4	1.4114	−0.07
ζ *Canis Majoris*	3.0	6 16 28	−30 01.2	95 59.1	1.2493	0.03

Star	Mag.	R. A.			Dec.		λ (1900)		log *b*	*c*
10 *Monocerotis*	4.9	6	23	01	− 4	42.0	96	30.0	1.4196	−0.04
ν *Geminorum*	4.2	6	23	02	+20	16.5	95	24.4	1.4731	−0.05
11 *Monocerotis* seq	5.5	6	23	58	− 6	58.2	96	53.6	1.4100	−0.03
ξ¹ *Canis Majoris*	4.4	6	27	41	−23	20.8	99	15.8	1.3109	−0.01
Lal. 12587	5.9	6	28	33	− 1	08.6	97	50.5	1.4331	−0.03
42 *Camelopardi*	5.1	6	40	32	+67	41.0	95	22.0	1.3276	−0.04
15 *Canis Majoris*	4.6	6	49	14	−20	06.0	105	51.0	1.3387	+0.03
o² *Canis Majoris*	3.0	6	58	51	−23	41.2	109	36.8	1.3144	+0.05
γ *Canis Majoris*	4.2	6	59	14	−15	29.1	108	13.0	1.3702	+0.05
ω *Canis Majoris*	3.7	7	10	45	−26	35.5	114	14.5	1.2944	+0.07
29 *Canis Majoris*	4.8	7	14	30	−24	22.5	114	52.3	1.3137	+0.08
16 *Argus*	4.2	8	04	34	−18	57.1	128	34.2	1.3682	+0.18
η *Hydrae*	4.2	8	38	00	+ 3	45.5	130	54.6	1.4601	+0.24
κ 76 *Cancri*	5.3	9	02	20	+11	04.2	134	46.4	1.4716	+0.27
S. D. − 8°.4010 *Librae*	5.0	15	29	02	− 8	50.8	232	08.5	1.4673	+0.37
τ *Librae*	3.9	15	32	31	−29	26.9	237	57.3	1.4670	+0.34
π *Scorpii*	3.1	15	32	48	−25	49.6	241	32.6	1.4717	+0.32
ω¹ *Scorpii*	4.1	16	00	57	−20	23.9	242	16.4	1.4737	+0.31
σ *Scorpii*	3.0	16	15	06	−25	21.2	240	24.2	1.4726	+0.28
τ *Scorpii*	2.9	16	29	39	−28	00.5	250	03.6	1.4712	+0.26
u 68 *Herculis*	5.0	17	13	40	+33	12.5	252	31.3	1.2217	+0.13
66 *Ophiuchi*	4.8	17	55	19	+ 4	22.4	268	40.5	1.4194	+0.10
96 *Herculis*	5.1	17	58	07	+20	50.0	269	23.0	1.3285	+0.07
102 *Herculis*	5.5	18	04	29	+20	48.0	271	27.6	1.3287	+0.06
φ *Sagittarii*	3.3	18	39	24	−27	05.6	278	47.0	1.4727	+0.02
δ¹ *Lyrae*	5.3	18	50	14	+36	50.8	290	00.4	1.1801	−0.04
18 *Aquilae*	5.0	19	02	16	+10	55.0	288	23.7	1.3954	−0.05
η *Lyrae*	4.8	19	10	21	+38	58.5	298	40.6	1.1635	−0.07
2 *Cygni*	4.8	19	20	11	+29	25.5	298	16.4	1.2733	−0.09
8 *Cygni*	4.8	19	28	03	+34	14.4	302	53.4	1.2301	−0.10
ι *Aquilae*	4.3	19	31	33	− 1	30.5	294	26.6	1.4466	−0.11
Lal. 38896	4.8	20	11	02	+25	17.2	312	50.4	1.3307	−0.19
P Cygni	4.9	20	14	06	+37	43.3	309	36.1	1.3096	−0.16
ω¹ *Cygni*	4.9	20	26	58	+48	36.9	334	38.7	1.1148	−0.18
57 *Cygni*	4.6	20	49	43	+44	00.5	336	32.8	1.1971	−0.22
G Cephei	5.7	21	09	16	+59	34.5	355	39.9	1.0458	−0.18
υ 66 *Cygni*	4.4	21	13	48	+34	28.6	335	52.4	1.3037	−0.27
A Cygni	5.1	21	14	44	+43	31.5	343	08.1	1.2289	−0.25
70 *Cygni*	5.2	21	23	17	+36	40.9	339	56.0	1.2944	−0.28
13 Hev. *Cephei*	5.7	21	35	51	+57	02.2	354	46.2	1.1190	−0.21
π¹ *Cygni*	4.7	21	38	33	+50	44.0	356	54.2	1.1887	−0.25
π² *Cygni*	4.3	21	43	06	+48	50.8	355	48.4	1.2106	−0.26
16 *Pegasi*	5.2	21	48	31	+25	27.5	20	10.0	1.3811	−0.40
2 *Lacertae*	4.5	22	16	54	+46	01.9	0	52.2	1.2698	−0.31
4 *Lacertae*	4.6	22	20	28	+48	58.1	4	29.6	1.2499	−0.30
6 *Lacertae*	4.5	22	26	10	+42	36.6	0	38.4	1.3031	−0.33
10 *Lacertae*	4.9	22	34	46	+38	31.8	358	59.4	1.3364	−0.36
β *Piscium*	4.3	22	58	47	+ 3	16.9	347	11.4	1.4683	−0.45
1 *Cassiopeiae*	5.0	23	02	23	+58	52.8	23	59.3	1.2124	−0.27
1 Hev. *Cassiopeiae*	5.0	23	25	25	+57	59.9	26	46.8	1.2433	−0.28
λ *Piscium*	4.4	23	36	57	+ 1	13.8	355	10.7	1.4729	−0.48
σ *Cassiopeiae*	5.0	23	53	56	+55	11.9	28	44.7	1.2871	−0.31

YERKES OBSERVATORY,
May 5, 1904.

MINOR CONTRIBUTIONS AND NOTES.

AN EXPEDITION FOR SOLAR RESEARCH.

WITH the aid of a grant of $10,000 from the Carnegie Institution, for use during the current year, the Yerkes Observatory has sent an expedition to Mount Wilson (5,886 feet) near Pasadena, California, for the purpose of making special investigations of the Sun. The principal instrument to be erected on the mountain is the Snow horizontal telescope, recently constructed in the instrument and optical shops of the Yerkes Observatory. This telescope is a cœlostat reflector, the cœlostat mirror having a diameter of 30 inches. A second plane mirror, 24 inches in diameter, reflects the beam from the cœlostat north to either one of two concave mirrors, each of 24 inches aperture. One of these concave mirrors, of about 60 feet focal length, is to be used in conjunction with a solar spectrograph of 5 inches aperture and 13 feet focal length; a spectroheliograph of 7 inches aperture, resembling the Rumford spectroheliograph of the Yerkes Observatory; and a stellar spectrograph provided with a large concave grating, and mounted in a constant temperature laboratory. It is hoped that it will be possible with this stellar spectrograph to photograph the spectra of a few of the brightest stars. For fainter stars, the spectrograph is to be provided with several prisms, for use singly or in combination.

The second concave mirror of the cœlostat reflector is designed to give a large focal image of the Sun, especially adapted for investigations with a powerful spectroheliograph, and for spectroscopic studies of Sun-spots and other solar phenomena. The focal length of this mirror is about 145 feet, so that it will give a solar image about 16 inches in diameter. The spectroheliograph is to be of 7 inches aperture and 30 feet focal length. For the present, until a suitable grating can be obtained, the dispersive train of this instrument will consist of three prisms of 45° refracting angle, used in conjunction with a plane mirror, so as to give a total deviation of 180°. The motion of the solar image, of which a zone about 4 inches wide can be photographed with the spectroheliograph, will be produced by rotating the concave mirror about a vertical axis by means of a driving-clock. A second driving-clock, controlled electrically so as to be synchronous with the first driving-clock, will cause the photographic plate to move behind the second slits. Three slits will be provided at this point, so as to permit photographs to be taken simultaneously through as many different lines of the spectra. It is hoped that this spectroheliograph will prove to be well suited for use with some of the narrower dark lines of the solar spectrum.

The work is to be under the immediate direction of Professor George E. Hale, Director of the Yerkes Observatory. During his absence Professor Edwin B. Frost will be in immediate charge of the Yerkes Observatory, with the title of Acting Director. Professor Frost will also be the managing editor of the ASTROPHYSICAL JOURNAL. Mr. Ferdinand Ellerman and Mr. Walter S. Adams, of the Observatory staff, will be associated with Professor Hale in the work at Mount Wilson.

Correspondents are requested to send all letters, books, or pamphlets intended for Messrs. Hale, Ellerman, or Adams to 678 St. John Avenue, Pasadena, California.

REVIEWS

Die Bilderzeugung in optischen Instrumenten vom Standpunkte der geometrischen Optik. Herausgegeben von M. VON ROHR. Berlin: Julius Springer. 1904.

THE appearance of the names of Czapski, König, Löwe, and others of the Carl Zeiss optical works in connection with a book edited by the author of the *Theorie des photographischen Objectivs* must necessarily mark an epoch in the theory of optical instruments. The work can, in fact, be called nothing less than encyclopædic in its range and completeness, and from the standpoint both of the student of geometrical optics and of the practical optician will prove of extreme value. The difficulty of finding a satisfactory treatment of the theory of the various aberrations when applied to lens construction is one which is familiar to all who have dealt with optical instruments, and it is to them that such chapters as that of König and von Rohr on spherical aberration, and those of König on chromatic aberration, and on the computation of optical systems, will especially appeal.

It is, of course, impossible to attempt to cover the contents of a work of this character within the limits of a brief review, and in the following we shall give only a general outline, with occasional reference to some of the more striking features. The choice of the latter, however, is by no means easy in the present case.

The first four chapters of the book are devoted to the consideration of the fundamental properties of geometrical rays and pencils when reflected or refracted at the surface of different media. The first chapter introduces the conception of the geometrical ray, and the general theorems of reflection and refraction, and under these, in turn, are discussed the important principles of the shortest path, or its modification, the shortest time, the law of Malus, and the mathematically valuable, although practically somewhat unrealizable characteristic function of Hamilton. The chapter closes with the definition of the cardinal terms in use with an optical system. The treatment throughout is thoroughly general and forms an admirable basis for the succeeding chapter, in which the course of the geometrical ray is followed through the optical system. The formulæ are here derived first for the simplest case of axial rays, and are then extended to meridional rays, and finally to rays with finite inclination to both of the axial planes.

In the third and fourth chapters the theory of the formation of optical images is considered. The former derives the general laws connecting object and image, while the latter discusses the cases which arise for different forms of the reflecting or refracting surfaces. The separation between telescopic images and those for objects of finite distance is made early in the treatment, and the relations deduced between them form one of the most interesting features of this part of the book. At the close of the fourth chapter are given a number of historical notices in regard to the material considered, an especially valuable bibliography being added under the subject of astigmatism.

With the the fifth chapter begins an extraordinarily complete and lucid discussion of the theory of spherical aberration, which can scarcely become other than a classic on the subject. Abbe's method of invariants is applied to the derivation of the formulæ for Seidel's aberrations, and the developments are carried as far as to the third power of the inclination in the case of non-axial rays forming a pencil of finite angular aperture. As is stated in the preface, a considerable part of this development is here carried out for the first time. The different aberrations are treated separately, a process which assists remarkably in giving clearness to this complex subject.

The chapter on chromatic aberration is comparatively brief. After a consideration of the size of the circles of aberration, and Gauss's method for determining the amount of chromatic variation for a given system in any case from a knowledge of its amount in a single instance, the author treats the different lens combinations in detail. A short but valuable section on the variations of spherical aberration with wave-length closes the discussion.

The seventh chapter, on the computation of optical systems on the basis of the theory of the aberrations, is of especial value as applying the material developed in the two previous chapters. The conditions for the elimination of each aberration are set out in detail, and the summary of formulæ under each separate case is of extreme practical value. At the close of the chapter two very interesting sections are appended; the first on the correction of outstanding aberration through the introduction of slight changes into the radii of curvature of the lenses; the second on the relation of eyepiece to objective in an optical system, and on the relative aberrations of similar systems in which the linear dimensions have an integral ratio.

Lack of space precludes a detailed summary of the contents of the remainder of the book. A chapter on prisms and prism-systems by Löwe is followed by a valuable discussion by von Rohr of the eye in its relation to optical instruments. The last chapter, also by von Rohr, is an application of photometric principles to optical systems, and contains many distinctly novel results. The book closes with a table of the symbols used in the course of the various developments, which will be found of decided convenience for reference.

The purely geometrical character of the treatment throughout the entire book is emphasized in the preface, and should be carefully borne in mind by the reader, who in many cases would do well to have a parallel course of reading in some treatise on physical optics. In conclusion attention should be called to the marked character of unity running through the work, which, in view of the great range of material, and the diversity of authorship, can be called nothing less than remarkable, and reflects great credit upon the editor, Dr. von Rohr. Finally, no review would be complete without some reference to the admirable press-work of the volume, and to the absence of typographical errors in a series of developments in which the extremely complicated system of notation would make such errors readily excusable.

W. S. A.

Cours élémentaire d'astronomie et de navigation. Par P. CONSTAN, professeur d'hydrographie de la marine. Première Partie, Astronomie (pp. vi+264), 1903. Deuxième Partie (pp. 296), 1904. Paris: Gauthier-Villars.

THESE two volumes, published at the request of Professor Constan's former pupils, contain everything that, in the author's opinion, need be known by a modern navigator. They compare very favorably with similar works in our own language intended for the same class of students. The present work is eminently practical, without slighting the necessary theory; the demonstrations are straightforward and simple, and the illustrations are models of clearness.

The author has sought to relieve the subject of some of the dryness it must inevitably have for the majority of students, by introducing occasional historical references. These, however, show a rather amusing bias toward the author's own countrymen. For example, the compensating pendulum is attributed to Leroy instead of Harrison;

the heliometer to Bouguer alone, instead of to Dollond and Savery as well; and the discovery of Neptune to Leverrier alone. The same bias is shown in the choice of numerical data: the author recommends Caillet's tables for refraction; he cites Faye's elements of the Earth's size and shape, and only Fizeau's and Cornu's determinations of the velocity of light.

F. S.

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